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SCINTILLATION COUNTERS

A DISSERTATION

SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

FACULTY - ENGINEERING

by

E. A. GODBY

EDMONTON, ALBERTA

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THE SCINTILLATION COUNTER

SUMMARY

The scintillation counter is a relatively new counter for the detection of nuclear and atomic radiations. Indications are that it will occupy a very important position in the nuclear field - its very short resolving time, high efficiency and energy discriminating capabilities, permitting nuclear particle measurements which were previously impossible. Seven 931-A photo-multiplier tubes in conjunction with naphthalene phosphors were investigated with a view to determining the basic properties of the counter, and possible future applications. In most cases the scintillation counter was compared with the conventional counter it most nearly resembles, and whose properties are well known - the geiger counter.

INTRODUCTION

One of the first methods of detecting nuclear radiations was by observing the flashes of light released when high energy alpha particles struck a fluorescent screen. By this means many classical experiments were performed. However, due to the fact that the eye was used as a detector of the emitted light, no accurate quantitative data could be obtained, and this method soon gave way to the geiger tube and the ionization chamber. With the advent of the photomultiplier tube however, it has been possible to restore this original method of detecting radiation by replacing the eye of an observer with a photomultiplier tube. The resulting detector has many great advantages, and for many purposes it may be found superior to the geiger counter. The chief advantages of the photomultiplier radiation detector are:

(1) extremely short resolving time

(2) high intrinsic efficiency

(3) high range of sensitivity

(4) energy discriminating properties

Although the detector is still in its infancy the above properties suggest that it will represent one of the most important advances in devices for the detection of nuclear radiations since the invention of the Geiger-Mueller counter. At the present time the scintillation counter is rather complicated and requires more elaborate circuitry than does the geiger counter. Simplification will undoubtedly be made along many lines however, and the result may be a counter no more involved than present conventional counters.

The scintillation counter in its simplest form is illustrated in Fig. I. When a nuclear particle is absorbed by the phosphor crystal it emits a flash of light. Many crystals have this property,[1-12-19] including

naphthalene, anthracene, and zinc sulphide (which are the most commonly used). The flash of light falls on the photo-cathode of the photomultiplier and releases photoelectrons, which by a multiplication process produce a current pulse at the output. This pulse is then amplified by a linear amplifier. Since the pulses will vary greatly in amplitude a pulse height discriminator is necessary to pass only those pulses having an amplitude above some predetermined value. These selected pulses are then fed into the Scaler, which gives one pulse for every 64 which enter. These output pulses from the scaler are recorded by a mechanical register. The counting rate is determined by observing the counts over a time interval.

EXPERIMENTAL EQUIPMENT

The pulse performance of the multiplier was measured by the amplifier discriminator, and scaler as shown in Fig. I. A photograph of the actual equipment used is shown in Fig. 17. A more detailed account of the equipment will now be given.

(a) Photomultiplier Tube 931-A

Fig. II shows the arrangement of the electrodes within the RCA931-A photomultiplier tube. Arrows show the paths of the electrons as they move between the electrodes under the influence of two dimensional electrostatic fields. The incident light impinging on the photocathode ejects photoelectrons which are swept to the first dynode by a potentional difference of about 100 volts. Each electron arriving at the first dynode produces 4 or 5 secondary electrons by the process of secondary emission and these are swept along to the second dynode by a 100 volt potential where the multiplication process is continued. The electrodes form a series of electron optical lenses, which prevent the electron from diverging during the multiplication process. After 9 such stages an avalanche of about a million electrons appears at the output of the multiplier tube as a result of each initial photoelectron.

Although the resulting pulse may be large enough to operate an oscilloscope directly, it is usually advantageous to further amplify the pulse by means of a linear pulse amplifier.

Dark Current Noise: One of the greatest problems associated with the utilizing of the photomultiplier as a particle counter is the dark-current noise. This dark current, is the current which appears at the output when no light falls on the photocathode, and is the sum of several contributing causes. First, and most fundamental, the electrode surfaces having a low work function, as is necessary for sensitivity to light and to electron bombardment, tend also to release electrons whenever they acquire the higher thermal velocities associated with molecular agitation even at room temperature. Thus a dark current of 10,000 to 100,000 thermal-emission electrons per second, depending on the particular tube, is emitted from the photocathode and from each dynode[1]. Only those emitted from the photocathode receive the full amplification of the tube and are of primary importance in contributing to noise. In order to be detected, the signal pulses must be as great or greater in number than the noise pulses. Even at low intensities the radiation may be detected if the signal pulses are greater in amplitude than the noise pulses. This may be accomplished by using a discriminator set at such a level that it will cut off most of the noise pulses and pass the higher amplitude signal pulses on to the scaler.

The noise due to thermal electrons decreases rapidly as the temperature is decreased, and much experimentation has been done at liquid air temperatures. Operating a counter at liquid air temperatures is for the most part impractical, and other methods must be used for distinguishing the signal from the thermal electron noise. This can be done by using efficient phosphors, good light collection, and by proper use of external circuitry.

The other two important contributors to dark current noise are: ohmic leakage over the insulators inside the tube and between lead wires at the tube base, and positive ion feedback. At about 110 volts per stage, an unstable region begins, which is due to regenerative positive in feedback between the photocathode and the last few multiplying electrodes.

(b) Phosphor

The phosphor is chosen for its efficiency in converting nuclear radiations into visible light, and data resulting from much experimenting is available on many materials.[2-13-19-24] To be an effective detector of any penetrating radiation (gamma and x-rays) the phosphor must have an appreciable thickness. This is understood when it is realized that a gamma ray which passes right through the crystal, produces no effect whatsoever; the photon must be absorbed to be effective, and the probability of it being absorbed increases with the thickness of phosphor through which it must pass. The crystal must also be transparent to the visible light produced by the absorption of a photon so that the light flash may be transmitted to the photomultiplier photocathode. Hence for gamma radiation a suitable phosphor is one which is (a) efficient in converting the gamma radiation into visible light (b) can be obtained in large massive pieces (c) is transparent to its own radiation.

The first materials successfully used for counting gamma and beta radiation were silver activated zinc sulphide, and naphthalene. Zinc sulphide has a high intrinsic efficiency (50% with x-rays) but its finely divided form prevents its being used in thick sections, and its relatively long decay time (20 micro-seconds) is prone to give rise to multiple counting. Since naphthalene fills the three above requirements of a good phosphor to a fair degree, many experiments have been performed with it and it has become a standard of comparison.

Fig. 3 illustrates the fact that an extremely wide range of photon energies as well as a large number of particle radiations can be detected by means of the scintillation counter equipped with the appropriate phosphor.

The flash duration time of naphthalene is 0.070 micro secs.[5] and that of anthracene is .035 micro secs.[5] at room temperature. Since these times are long, compared to the processes involved in the photomultipler, the resolving time of a scintillation counter can be made a small fraction of a micro second. This is to be compared with the 50 to 100 micro-secs. resolving time for the conventional geiger counter. This extremely short resolving time is one of the main advantages of this new counter over the conventional types.

Growth of Naphthalene Crystals: Large clear crystals of naphthalene can be obtained by slowly cooling the melt. This is easily done by lowering a test tube of naphthalene through a furnace at a rate of about 1 inch per 12 hours. Since the melting point of naphthalene is about 80°C, the furnace should be set at approximately 100°C. Using this method a clear crystal, 1cmx1cmx4cm, not entirely free from cracks, was obtained.

It should be noted that the test tube must be lowered through the furnace, and not raised. Naphthalene contracts much like paraffin wax upon solidifying, so that the process of solidification must proceed from the bottom upward if depressions due to contracting are to be prevented.

(c) Amplifier

The amplifier was the one described by J. W. Coltman[1], with the exception of one minor change which was made to better adapt it to the phosphor used (naphthalene). Fig. 4 is the basic circuit for introducing time constants R_1C_1 and R_2C_2, the purpose of which is to decrease the amplitude of the noise pulses below that of the signal. How this is accomplished

may be explained by means of Fig. 5.

(a) This shows a very large noise pulse at the left which can only be discriminated against with difficulty.

(b) a single pulse due to a beta particle has been added. Due to the persistence of the phosphor the pulse is spread over a considerable interval.

(c) This shows the effect of making R_1 large, so that the time constant R_1C_1 is 100 micro-secs. This integrates the pulses so that the signal pulse is well above the noise pulse. This time constant is too long and the maximum counting rate would be unduly low.

In Fig. 5 (d) the anode circuit time constant is set at 10 micro-secs. - equal to the decay constant of the screen. Now the counting rate is about as good as the decay time of the phosphor will permit, but the peak amplitude of the noise pulse is above that of the signal pulse.

Fig. 5 (e) By introducing condenser C_2 and making the time constant $R_2C_2 = R_1C_1$, a control is obtained on the rate of rise of potential. This damps out the initial fast rising swing of the noise pulse. Here the amplitude of the signal pulse is greater than that of the noise pulse, and a high counting rate has been maintained.

This method works well with a phosphor having a long decay time such as ZnS:Ag. When using a phosphor such as naphthalene which has a decay time of 10^{-8} sec., the condenser C_2 will only serve to decrease the pulse amplitude of both signal and noise, so that it is better left out. This was demonstrated by observing the waveforms of signal and noise pulses with and without C_2 in the circuit on a Lavoie trigger scope*. Fig. 6 shows the results obtained.

*Scope connection made to output of amplifier.

With C_2 in the circuit the pulses obtained were as shown in Fig. 6(a). No distinction could be made between signal and noise pulses.

Fig. 6(b) shows the pulses observed when C_2 was removed. Here again no distinction could be made between signal and noise pulses.

It can be concluded therefore, that the pulses produced by a light flash from naphthalene are of the same order of duration as a noise pulse, and therefore the above mentioned method cannot be used to separate them. The addition of condenser C_2 simply decreases the amplitude of both signal and noise pulses which is as undesireable as decreasing the amplification factor of the amplifier.

This would indicate that a phosphor with a long decay time has a certain advantage over those with extremely short duration, in that it affords a method of separating the signal from the noise. The disadvantage of course is that the maximum counting rate possible would be lower.

The complete amplifier as used is shown in Fig. 7. A high voltage supply variable from 700 to 1300 volts was available for the dynode potential divider. The 0.01 μf condensers across the bleeder at each of the last four dynode stages of the multiplier may be necessary to handle very large instantaneous currents during large signal pulses. The latter part of the circuit is a direct-coupled cathode follower stage to drive at low impedance the cable leading to the discriminator and counting circuits.

A very important practical consideration in the design and layout of the amplifier is the necessity for keeping the anode capacitance (shown dotted in Fig. 7) as low as possible. Since the voltage which appears on the grid of the 9001 is given by

$$V = Q/C \quad \text{where}$$

Q is the charge arriving at the anode of the photomultiplier,

and C is the anode capacitance, a large value of C will decrease the input grid voltage. By using direct coupling between the photomultiplier anode and the amplifier and by compact construction the anode capacity will be of the order of 10 $\mu\mu$f. This in conjuntion with a 1.5 meg grid resistor will result ina RC time constant of 15 micro-secs. which is not unduly great.

(d) Power Supply

The power supply for the photomultiplier potential divider was designed to deliver an external current of approximately 1-2 mils at a voltage variable from 800 to 1200 volts. A degenerative amplifier regulator was used on the output to insure against voltage variation due to line fluctuation. Since the fluctuation in load current is negligible at any one voltage setting, no voltage fluctuation due to this cause are observed. The necessity for a stable high voltage supply will be demonstrated when curves of noise current vs. voltage are considered.

(e) Pulse Height Discriminator and Scaler

The pulse height discriminator and the scaler are incorporated as one unit in the Atomic Instrument Company Model 101A Scaler.

RESULTS

The extreme variability of the noise pulse height distribution from one photomultiplier tube to another is demonstrated in Fig. 8. The curve of Tube #4 would ordinarily be located far to the right of the other curves, but in order to maintain a reasonable scale it was plotted at the top of the sheet. This variability is explained by the fact that it is very difficult to control accurately the properties of the photoelectric and secondary emission surfaces, and any factor which affects the sensitivity of all the surfaces is raised to the 10th power. Thus photomultiplier tubes intended for scintillation counting must be hand-picked if the ultimate in sensitivity is to be obtained. From the seven tubes tested #2 was selected as being the best adapted to the task of scintillation counting. The relatively low slope, as compared with the other tubes, indicated that it would be more stable with respect to discrimination setting. Any slight instability in the discriminator would not affect results too greatly. The signal to noise ratio exhibited by this tube was quite satisfactory.

The curves of Fig. 9 illustrate effectively the reason for employing a well stabilized high voltage supply in conjunction with the photomultiplier tube. A change in voltage of from 1000 to 1010 volts or 1% will change the observed noise count from 105 to 142 counts per minute or approximately 35%. This presents no real problem however, since well regulated power supplies can readily be obtained from dealers or can be constructed. The plans for a voltage supply ideal for this application can be obtained from Oak Ridge.[20]

At this point we might compare the relative stability of counting rate with voltage for the scintillation counter and the geiger counter. Whereas a scintillation counter, as was seen above, would exhibity a 35% change in counting rate for a 1% change in voltage, a geiger counter might be expected to exhibity .1 to .5% change in counting rate for the same 1% change in voltage.

In view of its greater stability with respect to voltage, the geiger counter can achieve the same precision of results as the scintillation counter while using a simpler and hence less expensive power supply. The effect of this would probably not be felt so much in equipment designed for the lab as it would in portable survey instruments. Here voltage changes, due to ageing batteries would show up markedly on a scintillation counter. Further research in the field of portable equipment will undoubtedly resolve this difficulty.

The ratio of two curves of Fig. 9 is shown in Fig. 10. This is a very important curve in as much as it illustrates the very marked dependence of signal to noise ratio on applied voltage. For this particular tube the optimum operating voltage is between 950 and 1000 volts, and operating outside this voltage will result in a marked decrease in signal to noise ratio. For some coincidence work it has been suggested that by using multipliers at voltages higher than their rated voltage, sufficient output signal can be obtained to operate coincidence circuits based on rectifying crystals (IN34) without amplification between the crystal and multipliers.[14] This has the advantage of greatly decreasing circuit complexities, and the large increase in signal to noise brought about by employing a coincidence system, would outweigh the disadvantage of operating at a higher voltage. This statement is made with the stipulation that voltage need not be increased too greatly to secure the required pulse size. Operating the counter at the unstable region which occurs at about 110 volts per stage would certainly result in a poor counter. This unstable region is explained by Allen.[8]

> "The unstable region beginning at 110 volts per stage is due to regenerative positive ion feedback between the photocathode and the last few multiplying electrodes. This effect increases with the residual pressure in the tube and may become so large as to maintain continuous oscillations within the electrode system."

This of course is the reason for the rapid decrease in signal to noise ratio with increased voltage, the pulses due to noise increasing more rapidly than those due to photoelectrons.

The signal to noise ratio as a function of the discriminator setting is shown in Fig. 11. Since a high signal to noise ratio is what is striven for in designing the counter, this curve would indicate that the discriminator should be set as high as possible. This means of obtaining a high signal to noise ratio is highly impractical however, and in order to obtain a true picture Fig. 11 must be considered in conjunction with Fig. 12. (Fig. 11 is the ratio of the two curves shown in Fig. 12.) At a discriminator setting of 10 a very good signal to noise ratio is obtained (Fig. 11) but from Fig. 12 we see that the Dark Current noise count is about 2 per minute at this setting. This would necessitate taking the background count over an unduly long time interval in order to determine the counting rate to any degree of accuracy. This may be realized from the following consideration.

It may be shown that if a total of N random counts is observed in any time interval, the expected deviation D from the true value will be given by $D = \sqrt{N}$. (Definition of D:- The probability of observing an error as large or larger than the Deviation D is .3173.) The "relative deviation" R.D. which is usually more instructive is merely the deviation or error expressed as a fraction of N. Thus R.D. = D/N

$$= \sqrt{N}/N = 1/\sqrt{N}$$

These relations are true for a Poisson frequency distribution, and although the dark current noise pulses from a photomultiplier do not strictly follow the Poisson distribution, as will be shown later, the above relations may be taken as an approximation.

Therefore, if 100 counts are observed the relative deviation is 1/ 100 = 10% i. e. there are 32 chances out of 100 that the deviation will be as large or larger than 10%. If 10,000 counts are observed the relative deviation is 1/ 10,000 = 1%. Thus it may be seen that if it is desired to count the Dark Current noise with a relative deviation of only 10%, 100 counts would have to be taken. At a counting rate of 2 per minute this would take 50 minutes. For a relative deviation of 1% the required counting time would be 83 hours.

It is quite obvious therefore that other methods must be found to increase the signal to noise ratio. A discriminator is necessary to eliminate the multitude of very small noise pulses, but discretion must be excercised in choosing the setting.

It may be noted from Fig. 13 that the photoelectron distribution differs from the Dark Current distribution. This may be explained as follows.

The dark current noise is the sum of several contributing factors, of which the most basic source is thermionic emission from the photocathode. These thermionic electrons are multiplied by the succeeding dynodes exactly as are photoelectrons and give rise to the same pulse height distribution. The dynodes are also thermionic emitters, but depending on which dynode is the source the electrons are amplified by less than the full gain of the multiplier and thus give rise to small pulses.

The rapid rise of the noise pulse curve near the zero pulse height limit of Fig. 13 indicate the presence of the multitude of small pulses. Since all the pulses due to photoelectrons receive the full amplification of the tube, the photoelectron pulse distribution curve does not exhibit this rapid increase.

STATISTICAL CONSIDERATIONS

(a) Photoelectron Pulse Height Distribution

In referring to photomultiplier tubes the secondary emission ratio, m, and consequently the gain, M, are usually considered as being constants whereas actually they are statistical quantities which vary accordin to some distribution function. The two important properties of any distribution are

(1) the expected or mean value

(2) the variance; (which expresses the variation in individual values about the mean)

We wish to find the way these properties are affected by the multiplicative processes of the photomultiplier tube.

The following symbols will be used:

x = number of electrons produced at the photocathode per flash of light

$m_o = E(x)$ = expected or mean value of x

y_i = number of secondary electrons produced for one primary (i'th) electron at the first multiplier

$m_1 = E(y_i)$ = expected number of secondary electrons produced for one primary (secondary emission ratio for the first multiplier)

$d_o^2 = \mathrm{Var}(x)$ = variance of x

$d_1^2 = \mathrm{Var}(y_i)$ = variance of y_i

m = average number of secondaries produced per primary at each of the succeeding (n-1) stages of multiplication

d^2 = variance in the number of secondaires produced per primary at each succeeding (n-1) stage of multiplication

$M = m_1 m^{n-1}$ = the overall multiplicator of the n stages of multiplication

The number of secondaries produced at the first multiplier for one flash of light is : $y = y_1 + y_2 + y_3 \ldots\ldots\ldots\ldots + y_x$ where x is the number of primaries.

$$E(y) = m_o\, m_1$$

$$E(y^2) = \underbrace{E(\, y_1^{\,2} + y_2^{\,2} + y_3^{\,2} \ldots\ldots + y_x^{\,2})}_{x \text{ of these terms}} + \underbrace{2y_1y_2 + 2y_1y_3 + \ldots\ldots)}_{\frac{x(x-1)}{2} \text{ of these terms}}$$

Since $E(y_1^{\,2}) = E(y_2^{\,2}) = \ldots\ldots\ldots = (d_1^{\,2} + m_1^{\,2})$

and $E(y_1y_2) = E(y_2y_3) = \ldots\ldots\ldots\ldots\ldots = m_1^{\,2}$

$$E(y^2) = (d_1^{\,2} + m_1^{\,2})\, E(x) \;+\; 2m_1^{\,2}\, E\left(\frac{x(x-1)}{2}\right)$$

$$= (d_1^{\,2} + m_1^{\,2})\, m_o + m_1^{\,2}\; E\left[(x^2) - (x)\right]$$

$$E(x^2) = d_o^{\,2} + m_o^{\,2}$$

$$E(y^2) = (d_1^{\,2} + m_1^{\,2})\, m_o + m_1^{\,2}\, (d_o^{\,2} + m_o^{\,2} - m_o)$$

$$\text{Var } y = D_1^{\,2} = E(y^2) - \left[E(y)\right]^2$$

$$= (d_1^{\,2} + m_1^{\,2})\, m_o + m_1^{\,2}\, (d_o^{\,2} + m_o^{\,2} - m_o) - m_o^{\,2} m_1^{\,2}$$

$$= d_1^{\,2} m_o + m_1^{\,2}\, d_o^{\,2}$$

The relative variance of $y = \dfrac{\text{Var } (y)}{\left[E(y)\right]^2}$

$$\frac{\text{Var } (y)}{\left[E(y)\right]^2} = \frac{D_1^{\,2}}{m_o^2 m_1^{\,2}} = \frac{d_o^{\,2}}{m_o^{\,2}} + \frac{d_1^{\,2}}{m_o m_1^{\,2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

This expresses the variance in electrons per pulse at the first multiplier stage. The same procedure may be carried out for each of

the (n-1) remaining stages in succession to obtain the variance in the number of electrons per pulse at the output of the tube. The expression is:

$$\frac{D_n^2}{m_o^2 M^2} = \frac{d_o^2}{m_o^2} + \frac{d_1^2}{m_o m_1^2} + \frac{d^2}{m_o m m^n}\left[\frac{(1-m^{n-1})}{(1-m)}\right] \quad \ldots\ldots\ldots\ldots(2)$$

Since $m^{n-1} \gg 1$ for a mutistage tube (2) becomes

$$\frac{D_n^2}{m_o^2 M^2} = \frac{d_o^2}{m_o^2} + \frac{d_1^2}{m_o m_1^2} + \frac{d^2}{m_o m_1 m(m-1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Ordinarily $m_1 = m$ and $d_1 = d$, so in this case

$$\frac{D_n^2}{m_o^2 M^2} = \frac{d_o^2}{m_o^2} + \frac{d^2}{m_o m(m-1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

This expression can usually be simplified if an assumption is made regarding the distribution of the photoelectrons and secondary emission electrons. If we assume that the secondary emission from a multiplying surface follows a Poisson distribution, then if m is the average or mean number of electrons being emitted when an electron strikes is:

$$p(x) = \frac{e^{-m} m^x}{x\,!}$$

The variance of this distribution equals the mean i.e. var (x) = m. The standard deviation = $\sqrt{m}$.

If we assume that the distribution of secondary electrons also follow the Poisson distribution then $d^2 = m$ and

$$\frac{D_n^2}{m_o^2 M^2} = \frac{1}{m_o} + \frac{1}{m_o(m-1)} = \frac{1}{m_o}\left[1 + \frac{1}{m-1}\right]$$

$$= \frac{1}{m_o}\,\frac{m}{m-1} \qquad \text{.....(6)}$$

It will be noted that this is the relative variance in the number of electrons per flash emitted from the photocathode $\left(\frac{1}{m_o}\right)$ increased by the amount $\left(\frac{m}{m-1}\right)$ due to the effect of the multiplier.

If the distribution of secondary electrons is other than that assumed above or if focussing losses are encountered, the variance in the secondary emission ratio m might be ε m instead of m. Making this assumption we obtain

$$\frac{D_n^2}{m_o^2 M^2} = \frac{1}{m_o}\left[1 + \frac{\varepsilon}{m-1}\right]$$

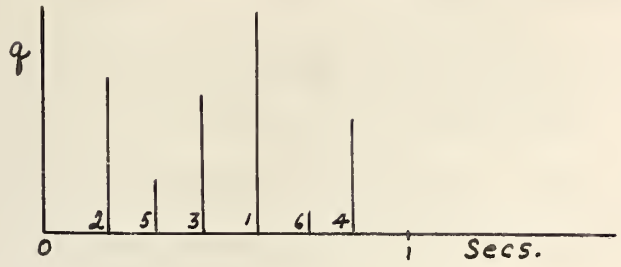
The correction factor ε can be evaluated from an integrated pulse height curve for photoelectrons as is shown by Fig. 13.

The Integrated Pulse Height Distribution

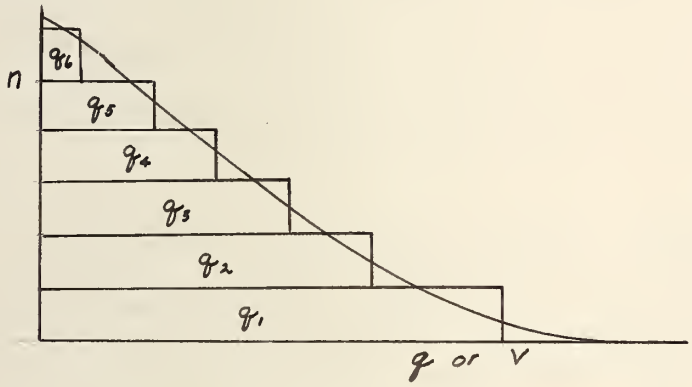
In the integrated pulse height distribution curve as shown in Fig. 13, the number of electrons actually entering the multiplier can be found by extrapolating the curve back to zero pulse height. This distribution can be used to calibrate the amplifier and count indicator in terms of electrons entering the multiplier as well as to determine the multiplier distribution characteristics.

The way in which the distribution curve is constructed might be considered at this point. If a number of pulses were observed on an

oscilloscope, say over a period of one second they might appear as follows



where the pulses are numbered in order of magnitude. To construct the integrated distribution curve the pulses are arranged according to magnitude. This is shown below.



The area under the curve, therefore, represents the total charge arriving at the anode in one second. This of course is the output current. The area under the curve = $\sum_{k=1}^{6} q_k$ = $\frac{\text{Total charge}}{\text{Second}}$ = i_o the output current. These pulses are normally measured in volts but they each represent a charge q_k coming out of the multiplier. The relation between the pulse height in volts v_k and q_k is

$q_k = CV_k$ where C = effective anode capacity.

It is desired to compare the variance in pulse height as determined experimentally with that derived from theory. The most advantageous way of doing this is to plot the cumulative frequency curve of Fig. 13 in units of the mean, rather than in volts. The variance of this normalized distribution will then be $\frac{D^2}{m_o^2 M^2}$ or the relative variance.

There are other advantages to plotting the distribution in this manner; the distribution will then be independent of: the gain of the photomultiplier, the amplification of the external pulse amplifier, and the coupling between the photomultiplier anode and the amplifier. This may be better understood if we consider the mean pulse in volts as being due to the mean number of electrons per pulse emitted from the photocathode, being multiplied by the mean gain of the multiplier and finally being amplified by the external amplifier. If we divide through by this mean voltage, we obtain a distribution with a mean value of one. This mean value can be considered as being due to one electron leaving the photocathode and being multiplied by a gain of one.

When using this distribution the concept of partial electrons or electrons of different heights, having a mean value of one electron, leaving the photocathode can be used. These partial electrons, with a mean of one, are multiplied by a gain which varies about a mean value of one. Hence we may consider the abscissae of this distribution as being in terms of electron heights. Fig. 14 shows the cumulative frequency distribution plotted in this way.

For the curve of Fig. 13 the mean pulse height is found by taking the area under the curve in volt counts per minute and dividing by the total pulses per minute entering the multiplier. The area under the curve of Fig. 13 was found by counting squares to be 22,090 volt counts per minute. The total pulses per minute (N) were 8500, giving a mean pulse height of 2.36 volts. Dividing the abscissae values of this distribution by 2.36 resulted in the distribution of Fig. 14.

To obtain the variance of this distribution we must use the frequency distribution curve corresponding to this cumulative or integrated

frequency distribution. If the equation of the integrated frequency distribution is $n = f(p)$ and the equation of the frequency distribution curve is $n_1 = F(p)$ then

$$F(p) = -f^1(p)$$

the variance of this distribution is

$$\frac{D^2}{m_o^2 M^2} = \frac{1}{N}\int_o^\infty F(p)(p-1)^2 dp$$

$$= \frac{1}{N}\int_o^\infty -f^1(p)(p-1)^2 dp$$

where 1 is the mean value of p

This expression may be simplified somewhat. Integrate by parts.

$$u = (p-1)^2 \qquad dv = -f^1(p)dp$$

$$du = 2(p-1)dp \qquad v = -f(p)$$

$$\frac{1}{N}\int_o^\infty -f^1(p)(p-1)^2 dp = \frac{(p-1)^2}{N} f(p)\Big]_o^\infty + \frac{2}{N}\int_o^\infty f(p)(p-1)dp$$

consider

$$-\frac{(p-1)^2}{N} f(p)\Big]_o^\infty = \frac{1}{N}\Big[-p^2 f(p) + pf(p) - f(p)\Big]_o^\infty$$

$\lim_{p\to\infty} p^2 f(p) = 0$ since $f(p)$ is of the form e^{-p} (See Fig.12)

Similarly,

$\lim_{p\to\infty} pf(p) = 0$

$$\frac{1}{N} f(p)\Big]_o^\infty = -\frac{1}{N}\Big[0-N\Big] = 1$$

$$\frac{1}{N}\int_o^\infty -f^1(p)(p-1)^2 dp = 1 + \frac{2}{N}\int_o^\infty f(p)(p-1)dp$$

The integral $\int f(p)(p-1)dp$ can be evaluated from the graph by picking out values of f(p) at equal intervals Δp and multiplying by the corresponding values of $(p-1)\Delta p$ and summing.

For Fig. 15 the value of this integral was found to be - 2,095.

$$\frac{D^2}{m_o^2 M^2} = 1 + \frac{2}{N}\left[- 2{,}095\right] = 1 - \frac{2}{8500} \times 2095$$

We can now obtain the value of ε from the known value of $\frac{D^2}{m_o^2 M^2}$ and by assuming a special case in the number of electrons per pulse emitted from the photocathode. Assume one electron per flash of light is emitted from the photocathode. In this case $d_o = 0$ and $m_o = 1$. Expression (4) becomes

$$\frac{D_n^2}{M^2} = \frac{1}{m-1}$$

However if the standard deviation for secondary emission is taken as ε m then the variance becomes

$$\frac{D_n^2}{M^2} = \frac{\varepsilon}{m-1}$$

therefore $$0.507 = \frac{\varepsilon}{m-1}$$

For a 931A photomultiplier operating at a gain of 10^6, the secondary emission ratio is

$m = (10^6)^{1/9}$ since there are nine stages

$m = 10^{2/3} = 4.57$

Therefore $\varepsilon = 1.81$

Thus the relative variance in the electrons per pulse is 1.81 times what would be expected if the number of secondary electrons emitted per primary electron followed the Poisson distribution. This indicates a very large variation in the spread of pulse heights. The deviation from what would be expected from the Poisson distribution might be due to electrons being lost in the process (focussing losses) or the actual distribution being other than Poisson.

Although the assumption of one electron per pulse made by G. A. Morton[14] is not strictly warranted, the value of $\mathcal{E}$ agrees with the results obtained by other authors[5] who stated that the observed spread in pulse heights was about twice the value as indicated by the Poisson distribution. The above results can be used to obtain a better understanding of the operation of photomultipliers.

Valuable information regarding the operating of the multiplier may be gained from considering expression (3)

$$\frac{D_n^2}{m_o^2 M^2} = \frac{d_o^2}{m_o^2} + \frac{d_o^2}{m_o m_1^2} + \frac{d^2}{m_o m m_1 (m-1)}$$

Let us assume that single thermal electrons are emitted from the photocathode, then

$$d_o = 0, \quad m_o = 1, \quad m_1 = m = 4.57$$

$$d_1^2 = d_2^2 = 1.81 \times 4.57 = 8.26$$

$$\frac{D_n^2}{M^2} = \frac{8.26}{1 \times (4.57)^2} + \frac{8.26}{1 \times 4.57 \times 4.57 \times 3.57}$$

$$= \frac{8.26}{20.9} + \frac{8.26}{74.8}$$

$$= .39 + 0.11 = 0.50$$

This indicates that most of the noise originates in the first multiplication process, and the distribution of pulse sizes is very broad. The relative variance gives a measure of the noise produced since it is the variation in noise pulse height, and not the mean height, that causes the difficulty in scintillation counting. Noise pulses amplitude distributed over a very small range could quite easily be discriminated against. Hence, when taking precautions regarding noise, much attention must be paid to factors (eg. voltage), affecting the first stage of multiplication.

Assume now that a naphthalene crystal is used in conjunction with the photomultiplier and the mean number of photoelectrons per pulse is 10. If the flucuations about this number follow a Poisson distribution

$$d_o^2 = m_o$$

$$\frac{D_n^2}{m_o^2 M^2} = \frac{1}{10} + \frac{8.26}{10 \times 4.57 \times 3.57}$$

$$= 0.1 + .05 = .15$$

In this case the fluctuations due to the variation in the number of photoelectrons per pulse, will be of the same order of magnitude as the fluctuations due to the multiplicative process. If the average number of photoelectrons per light flash is 100 rather than 10, the relative variance in the ouput will be

$$\frac{1}{100} + .005$$

$$= .015$$

This represents a rather narrow distribution in pulse sizes, which is a desireable situation. Hence much effort should be spent in producing good phosphors of high physical efficiency, and in collecting as much of the light as possible.

(b) Counting Rate Distribution

While observing the background count from the photomultiplier tube, it was noted that the deviation in readings obtained was greater than might be expected assuming a Poisson distribution of pulses. This observation was facilitated by using graphs, which are available,[9] and allow speedy determination of the 90% or 95% error of counting rate determination when the average counting rate and length of time counted are known. (The 95% error is the error which would be expected to be exceeded 5% of the time, or in other words the probability of observing an error as great as or greater than the 95% error is 0.05.)

The distribution of the background counting rate was obtained by observing the number of counts in a 10 second interval, for 553 readings. The results of this determination are shown in Fig. 15. The mean counting rate $\bar{x}$, for this observed distribution was determined by taking

$$\bar{x} = \frac{1}{N}\sum_{i-1}^{K} f_i x_i, \text{ where}$$

f_i is the frequency of occurence of a counting rate of x_i, and N is the total frequency (553). The sum is taken from i= 1 to K, where K is the number of classes, or the number of different frequencies. From this value of the mean the theoretical Poisson distribution was plotted. Since the mean is the only parameter occuring in the Poisson distribution, the distribution is fully defined when the mean is known. This theoretical curve is shown plotted with the observed distribution. Upon first inspecting the two curves, they would appear to be in fair agreement, but in order to obtain a quantitative result of the goodness of fit, the Chi-square test was applied. The Chi square (χ^2) test is useful in determining whether or not an observed distribution can be reasonably supposed to have arisen from random variations in theoretical distribution.

χ^2 is defined by the relation

$$\chi^2 = \frac{(f_o - f_c)^2}{f_c}$$ where

f_o is the observed frequency

f_c is the calculated frecuency

Having calculated the value of χ^2 corresponding to a given number of determinations, it is possible to determine the probability that the observed distribution is a reasonable one to expect, if the variations are due only to the randomness in the theoretical distribution. This probability (P) has been calculated as a function of χ^2 and the number of degrees of freedom (degrees of freedom = K-1 where K is the number of classes.) It must be noted that the χ^2 test is not valid for frequencies of less than five, so that frequencies of this order must be grouped with the one above. This, of course, reduces the number of classes. The value obtained for χ^2 was 47.314 with 25 - 1 = 24 degrees of freedom. Entering tables with these values, the probability (P) was found to be .0068. This means on the hypothesis that the observed curve is a Poisson distribution, a discrepancy as great as, or greater than the one actually observed, would be expected to occur about .0068 of the time, or about 7 times out of 1,000. This may be clarified by the following quotation from R. A. Fisher:

> "In preparing tables of P vs. χ^2 it is borne in mind that we do not want to know the exact value of P for any observed χ^2, but in the first place whether or not the observed value is open to suspicion. If P is between 0.1 and 0.9 there is certainly no reason to suspect the hypothesis tested. If it is below 0.02 it is strongly indicated that the hypothesis fails to account for the whole of the facts. We shall not often be astray if we draw a conventional line at 0.05 and consider the higher values of χ^2 indicate a real discrepancy".

Since the observed value of P is well below .05 we can say that it is very improbable that the observed distribution is Poisson.

From Fig. 16 the reason for the large value of χ^2 resulting in a small value of P can be seen. The observed readings at the tail of the distribution depart from the theoretical values to a considerable extent. The tail of the observed distribution is longer, indicating a greater spread in the counting rate.

Here, when observing the background counting rate from a photomultiplier tube, a greater variation in counting rate must be expected, than that indicated by a Poisson distribution.

ALPHA AND BETA COUNTER

Since the scintillation counter is so admirably suited to counting alpha and beta radiations, an experimental model was constructed for this purpose.

The chassis used was a standard 7" x 4" x 2" Hammond model complete with bottom plate. All components were mounted within the chassis, the photomultiplier tube being contained in a light proof housing. The amplifier had of necessity to be in close proximity to the photomultiplier tube, in order to keep the anode capacity low, and also to provide a cathode follower to drive the cable leading to the discriminator and scaler at low impedance. A photograph of the complete probe unit is shown in Fig. 18. A very thin light proof window must be provided which will allow the alpha particles to reach the phosphor. Since Aluminum can be obtained in the form of very thin opaque foil it is ideal for this purpose. An additional advantage is its shiny surface which acts as a good reflector for the light emitted by the phosphor.

Curves of the range of alpha particles in Aluminum as a function of their energy are available [10] and from this information the maximum thickness of Aluminum permissable for the windows can be computed. The minimum energy of alpha particles from a radium source is 4.78 Mev.[12] For these alphas the range in Aluminum is 5 Mg/Cm^2. or .005 /2.7 x 2.54 =.00073". Foil somewhat thinner than this is therefore necessary. The thinnest foil a available from the Aluminum Company of Canada was .00023" and this being about 1/3 the maximum permissable and was considered quite satisfactory. Care must be excersied to see that the piece of foil used does not contain any pin point holes. To protect the foil from the outside and also to support it, a piece of brass screening was used. This is shown as Fig. 4 in the photograph. This screen was soldered into a recess in the copper frame marked 3.

The phosphor, which cannot be seen in the photograph, is contained in a square hole cut in the part marked 5, and is exposed to the photomultiplier tube through a hole cut in the chassis. A thin wafer of naphthalene 3 cm x 3 cm x 1 mm, was used as the phosphor. In counting alpha and beta particles it is desirable to use a very thin crystal to decrease the efficiency for gamma rays. This is of advantage when the source emits gamma rays along with the alpha or betas, and it is desired to reduce their count to a low value. The light from the phosphor was conducted to the photocathode of the photomultiplier tube by the aluminum stack marked 2. The entire housing containing the photomultiplier tube is made light proof by a rubber gasket between the chassis and the cover.

The photomultiplier tube potential divider is contained in the second compartment (6) along with various other components of the amplifier. The amplifier tubes were placed in the position shown so that only a very short lead would be needed to connect the photomultiplier anode to the grid of the amplifier tube. The amplifier circuit, the diagram of which is shown in Fig. 7 was described previously.

The auxiliary apparatus necessary to operate the counter is:

(a) High voltage supply for the photomultiplier tube. The external connection for this supply is shown in Fig. 18 by 7. A coaxial cable is used for this lead.

(b) Power supply for the amplifier. This supply for the amplifier was obtained from the scaling unit used, which provides an outlet for auxiliary electron apparatus. The power plug is numbered (8). This plug also carries the connection for the pulse cable.

(c) Discriminator and scaling unit.

The counter with its auxiliary apparatus is shown in Fig.19. On the left is the high voltage supply, and on the right is the scaling unit and discriminator. On top of the scaling unit is the mechanical counter. In front of the counter window is a piece of pitchblende ore.

Only one curve was taken to illustrate the effectiveness of the counter. Since it is known that alpha and beta particles are absorbed very readily, placing a thin sheet of metal between the source and counter should decrease the counting rate to a low value. If a source which emitted only alpha and beta particles were available the count should decrease to the background value when the absorber is inserted. However, a pure source was not available so a radium source which emits alpha, beta and gamma radiations of varying energies was used. The absorption curve obtained is shown by Fig. 16. To obtain this curve .007 inch brass absorbers were used. The maximum alpha particle energy from the source employed was 7.68 Mev. and these have a range of 11 Mg./cm^2 aluminum[10], or approximately $\frac{.011}{8.5 \times 2.54}$ = .00051 inches of brass. Hence it is obvious that the first absorber of .007 inches would cut out all alpha particles and certainly some betas. This is borne out by the fact that the count drops from 8,200 to 500 counts per minute or by 94% when the first absorber is inserted.

Absorbers 2, 3 and 4 cut the counting rate down from 500 to 70 counts per minute and this is mostly due to the absorption of beta particles and in some measure to the absorption of soft gammas. This may be shown from the following table of beta emitters in the Radium Series.

Element	Energy of Beta Radiation Mev[12]	Maximum Range gms/cm^2[11]	Maximum Range in Brass Mils	No. of 7 Mil Absorbers Maximum Energy Beta will penetrate
RaB	0.65	.22	10.2	1.45
RaC	3.15	1.6	74	10.6
RaC''	1.80	.86	40	5.7
RaD	0.025	negligible	negligible	0
RaE	1.17	0.5	23	3.3

From the appearance of the curve, it would seem that nearly all the beta particles had been absorbed by absorbers 1 to 4. However, we see from the table that the beta particles from RaC should penetrate 10 thicknesses of absorber. This apparent discrepancy may be explained by considering the absorption curve for beta particles given off by a pure beta emitter. In this case we have a continuous distribution of beta particles with various energies. The absorption curve looks somewhat like an exponential curve. The intensity falls off sharply for small thicknesses of absorber since the low-energy beta particles are rapidly absorbed. Unlike gamma rays the beta particles have a definite maximum energy, and it is the range of this maximum energy beta that is given in the tables. Hence, even though some betas do undoubtedly penetrate ten of the absorbers the greater majority of them have been absorbed before they reach the fifth absorber. In addition to this, we must consider the other three emitters RaB, RaC'', and RaE which add to the total beta count.

Nearly all the betas from RaB would be absorbed by absorber No. I and the rest by absorber No. 2. Some betas from RaC'' would penetrate five absorbers, but here again very few would pass the fourth absorber. The betas from RaE would be completely absorbed by the first four absorbers. Hence for all intents and purposes the beta particles are all absorbed before absorber 5. Tho straight line through absorbers 4, 5, 6 and 7 would indicate absorption

of gamma rays. Undoubtedly some beta rays penetrate to this region and beyond but these are sparse and well masked by the count due to gamma rays.

Much more interesting experimental work could be done with standard alpha, beta and gamma sources. However, this curve discussed does indicate the fact that the counter is effective in counting alpha and beta particles, and that is the main consideration.

One of the strong points of this counter is its simplicity, which would allow it to be built in any workshop. A geiger counter designed to perform a similar task would be complex in comparison and would require special techniques both in construction and use. This counter is extremely rugged and both the photomultiplier tube and the phosphor have indefinite life. This is compared to a self quenching geiger counter, whose life is limited by the number of counts - usually about 10^8.

The counter can be used by students and relatively untrained personnel, without fear of damaging the unit, since there is no thin mica window to be broken, as in the case of the ordinary geiger beta counter. This unit is fairly portable in that the probe is at the end of a cable which can be made almost as long as desired. This means the counter can be taken to the source instead of having to bring the source to the counter as is necessary in practically all other alpha counters.

Very great improvements could be made along many lines. Phosphors more efficient for counting alpha particles can be used, and better methods of light collection devised. The amplifier could be reduced in size somewhat, allowing a smaller probe unit to be used. If a rate meter containing a high voltage supply were employed instead of the scaler this would obviate the necessity of using a power supply in a separate unit, hence only one piece of apparatus would be required in addition to the probe unit.

ADVANTAGES OF THE SCINTILLATION COUNTER AND POSSIBLE FUTURE APPLICATIONS

High Counting Rate

The maximum counting rate obtainable with a scintillation counter, is, at present, limited by the auxiliary electronic apparatus, and not by the counter itself. Hence further advances can be expected in the speed of scintillation counters by refinements in electronic apparatus, whereas the geiger counter has a fundamental limitation placed upon it, and any forseeable improvements will be small.

Even in the field of moderate counting rates, the scintillation counter will provide a certain simplification. Where accurate counting rate determinations are to be made by geiger counter, such as in assaying radioactive ores, the resolving time of the counter must be accounted for. With a scintillation counter the resolving time could be neglected entirely, hence eliminating one possible source of error.

High Efficiency for Gamma Rays

The efficiency of the geiger counter is of the order of $\frac{1}{2}$ of 1%, for hard gamma rays. This is due to the fact that the absorbing medium is a gas, so that the chance of a gamma ray being absorbed while traversing the tube is small. Here again the geiger tube is fundamentally limited. Using a greater number of geiger tubes may help to some extent but this of course, increases the background to cosmic rays, keeping the signal to noise ratio approximately the same.

The scintillation counter has a definite advantage in this field: the phosphor is a highly absorbent solid, so has an efficiency for gamma rays, several orders of magnitude greater than the geiger tube. (Screens several centimeters thick give efficiencies of 30% for counting 1.2 Mev Gamma Rays and higher for softer Gamma rays.[15]) This is a very important factor when low intensity, high energy gamma sources are to be detected.

This problem is met in the detection of radioactive ore bodies from the air. Here, only the hard components of the gamma rays are present, the softer components having been filtered out by the air. Since it is desireable to fly as high as possible, both for safety's sake and for the sake of accurate navigation, the efficiency of the detector is of paramount importance. The intensity of the rays decreases rapidly with altitude, due both to the inverse square law effect, and air absorption, and even doubling the efficiency of the counter would greatly increase the effectiveness of the apparatus. The scintillation counter can be expected to do much better than this (approximately 20-40 times), the limit being determined by the size and clarity of the crystal grown. Favoring the use of scintillation counters for airborne operations is the small volume they occupy, and their light weight as compared with the geiger counter.

The ever-present factor which limits the application of the geiger counter to detecting radioactivity from the air is the cosmic ray background. The geiger counter is about 99% efficient in detecting cosmic rays, and the scintillation counter efficiency would not be far different. The great advantage of the scintillation counter in this respect is its small volume and consequent low background due to cosmic rays. Consider a geiger counter and a scintillation counter which indicate the same number of signal counts from a given gamma source. The phosphor of the scintillation counter would have about one-thirtieth the volume of the geiger counter, due to the difference in efficiencies for gamma rays. However, both would have an efficiency approaching 100% for cosmic rays. Due to the small volume of the phosphor, the scintillation counter would register 1/30 as many cosmic rays as the geiger counter. Hence the signal to noise ratio for the scintillation

counter would be 30 times as great as that of the geiger counter. Since the signal to noise ratio is the main factor which determines the relative merits of a counter, the scintillation counter is seen to have a tremendous advantage over the geiger counter for this application. A factor which has been neglected is the dark current noise of the photomultiplier tube, which would decrease the above advantage somewhat, but on the other hand a more efficient crystal which would raise the above estimate from 30 to say 50 is conceivable.

Well Adapted to Alpha and Beta Counting

In the scintillation counter the phosphor is in an exposed position external to the vacuum envelope of the phototube, and requires no difficult thin window techniques with easily absorbed radiations like alpha rays, beta rays and soft x rays. In the geiger counter tubes the radiations must pass through a wall which is capable of withstanding the difference in pressure between the outside and the inside of the tube. This leads to complications and many specialized techniques are needed to count low energy radiations. In the scintillation counter the situation is very different, and as was shown, a counter can be constructed which is very rugged, and will detect alphas and betas with little difficulty. Here, the limitation is set by the thickness of the thin aluminum window. For lower energies however it would be quite simple to remove the aluminum window and extend the light proof housing so that the sample could be placed within it. This is simple technique, and would eliminate any absorption between the phosphor and sample.

Well Adapted to Localizing Activity to Small Area

Problems are encountered in biology and medicine where it is desired to determine accurately the position of a small source. Geiger counters are limited as far as physical dimensions are concerned so that it is sometimes difficult to accurately localize activity. A scintillation counter employing

a small phosphor on the end of a probe would be admirably suited to this task. The sensitive end of the probe could be made a very small area and all bulky apparatus could be remote from the phosphor. Experiments have been successfully carried out in "piping" light from the phosphor to the photo-multiplier tube, when the two are located some distance apart.[2] This is accomplished by using a hollow tube with highly polished metal surfaces or a solid rod of quartz or lucite.

Long Life

The scintillation counter has an indefinitely long life, as compared with the self-quenching geiger tube, who's life is limited by the number of counts (usually about 10^8). When the overall cost is a major consideration this might well be a deciding factor when considering which type of counter to purchase.

CONCLUSIONS

The conclusions which can be drawn from this paper have been summarized below:

(1) Photomultiplier tubes are extremely variable from one sample to another, and hence tubes to be used as scintillation detectors should be hand-picked if the ultimate in sensitivity is to be obtained.

(2) The signal to noise ratio varies greatly with applied voltage so that the optimum operating voltage must be determined for the tube used. The voltage supply must be well stabilized.

(3) The distribution of pulse heights at the photomultiplier anode is greater than would be expected, assuming a Poisson distribution of photoelectrons and secondary electrons.

(4) A discriminator is necessary to eliminate the multitude of very small pulses produced by the photomultiplier.

(5) Most of the noise originates in the first stage of multiplication and hence factors affecting this stage must be carefully controlled.

(6) The greater the number of electrons released from the cathode per flash of light, the narrower the distribution of output pulses. Hence it is desireable to use crystals of high efficiency and as good light collection as possible, so that each nuclear particle will result in a large flash of light falling on the photomultiplier photocathode.

(7) The dark current noise counting rate does not vary according to the Poisson distribution - the actual distribution of counting rate being wider than that to be expected from a Poisson distribution. Hence when using graphs or nomographs of the 90% or 95% error constructed on the assumption of a Poisson distribution, the results will not be strictly correct but will be smaller than that actually observed.

(8) The counter makes alpha and beta counting much simpler than was hitherto possible.

(9) Penetrating radiations (gamma rays and x-rays) can be counted with a much higher efficiency than was possible with the geiger counter.

(10) Higher counting rates than were hitherto possible can be used. Coincidence resolving times as short as 0.1 micro sec. can be used without measureable loss.

REFERENCES

1. Marshall, Coltman and Bennett	Photomultiplier Radiation Detection R.S. I. 19, 744 November 1948.
2. Bell	The Use of Anthracene as a Scintillation Counter. Physical Review,73 1405, June 1948
3. Coltman	The Scintillation Counter. Proceedings of the I.R.E. Vol.37 No.6 pp 671-682. June 1949
4. J. S. Allen	Particle Detection with Multiplier Tubes. Nucleonics. Vol.3 No. I. pp 34-39 July 1948
5. G. A. Morton and J.A. Mitchell	Performance of 931-A Type Multiplier in a Scintillation Counter R.C.A Review Vol. 9, No.4, Page 632 December 1948.
6. W. H. Jordan and P. R. Bell	Scintillation Counters. Nucleonics Vol. 5. No. 4, Page 30, October 1949
7. B. Cassen, C. W. Reed, L. Curtis, and L. Baurmash	Low -Rate Alpha Scintillation Counter Nucleonics Vol. 5 No. 4 Page 55 October 1949.
8. J. S. Allen	Recent Applications of Electron Multiplier.Tubes. Proceedings of the I.R. E. Vol. 38. No. 4 Page 346 April 1950.
9. A. A. Jarret	Statistical Methods Used in Measurements of Radioactivity. United States Atomic Energy Commission Document. No. AECU-262. June 1946
10.Lapp and Andrews	Nuclear Radiation Physics Text (1949) Prentice-Hall Inc. New York N.Y. Fig. 8-11, Page 168
11. Lapp and Andrews	As above -Fig.8-18 Page 180
12. Lapp and Andrews	As above Table 6-2 Page 110
13. Cornell Symposium of American Physical Society	Preparation and Characteristics of Solid Luminescent Materials.(1948)
14. G. A. Morton	Photomultipliers for Scintillation Counting.R.C.A. Review. Vol.10 No. 4. P. 525. December 1949

REFERENCES

15. M. Deutsch — High Efficiency, High Speed Scintillation Counters for Beta and Gamma Rays. Physical Review. Vol. 73,No.10 Page 1240 January 29, 1948.

16. H. Kallman — Quantitative Measurements with Scintillation Counters. Physical Review Vol. 75. No. 4, Page 623. Feb.15, 1949.

17. M. Blau and B. Dreyfus — The Multiplier Photo-Tube in Radioactive Measurements. R.S.I. Vol.16 No. 9 Page 245, Sept. 1945

18. J. S. Allen — An Improved Electron Multiplier Particle Counter. R.S.I. Vol. 18. No. 10, Page 739, October 1947.

19. R. J. Moon — Inorganic Crystals for the Detection of High Energy Particles and Quanta. Physical Review, Vol.73,Page 1210, May 15, 1948.

20. U. S. Atomic Energy Commission — A 160/1500 Volt Regulated Power Supply Bulletin, MDDC-778.

21. L. Wouters — Solid Counters: Scintillation Counters United States Atomic Energy Commission Bulletin AECD-2203. Technical Information Division, Oak Ridge Directed Operations AEC Oak Ridge, Tenn. 9-22-48-1250

22. A. H. Snell and L. C. Miller — The Secondary Electron Multiplier as a Particle Counter. United States Atomic Energy Commission Bulletin. AECD-1956. Technical Information Branch, Oak Ridge, Tenn. 3-1-49-200 -A1697.

23. R. F. Taschek and H. T. Gittings — Observations of Naphthalene Scintillations Due to Tritium Beta Rays. United States Atomic Energy Commission Bulletin AECD-2273. Technical Information Branch, Oack Ridge Tenn. AEC, Oak Ridge, Tenn. 4-11-49 850-A4936

REFERENCES

24. R. F. Taschek — The Relative Sensitivities of Some Organic Compounds for Scintillation Counters. United States Atomic Energy Commission Bulletin AECD-2353. Technical Information Branch, Oak Ridge, Tenn. 5-2-49-850-A1331.

25. J. C. Alley — A Method of Preparing Anthracene Crystals Suitable for Scintillation Counters. United States Atomic Energy Commission Bulletin AECD-49. Technical Information Branch, Oak Ridge, Tenn. 9-13-49-200-A15232.

26. P. R. Bell and R. C. Davis — Scintillation Counting with Anthracene. United States Atomic Energy Commission Bulletin AECD-1889. Technical Information Branch, Oak Ridge, Tenn. AEC, Oak Ridge, Tenn. 9-19-49-200-A-15862.

27. G. M. Brownell — Prospecting With a Scintillometer - Reprinted from The Precambrian, March 1950.

APPENDIX

Definition of Terms Used

Intrinsic Efficiency

The ratio of the energy emitted by an atom in the form of visible light to the energy of the incident particle or ray e.g., if a 1 Mev. gamma ray is absorbed by an atom of a particular phosphor, and .5 Mev. of visible light is emitted as a result, the intrinsic efficiency of the phosphor is 50%.

Efficiency

Ratio of the energy of visible light emitted from the phosphor, to the energy of the incident gamma radiation. This is a function of the thickness and clarity of the crystal, as well as of the intrinsic efficiency.

Regenerative Positive Ion Feedback

This phenomenon occurs when the voltage between stages is unduly high, resulting in positive ions produced at the last stages of multiplication, being drawn to the photocathode, and there producing secondary electrons, which are amplified in the ordinary way. This phenomenon must be guarded against since it greatly increases the noise background.

Pulse Performance

This simply refers to the characteristics of the pulses produced by the photomultiplier, and is concerned with

(1) distribution of pulse heights

(2) pulse width

(3) pulse rate

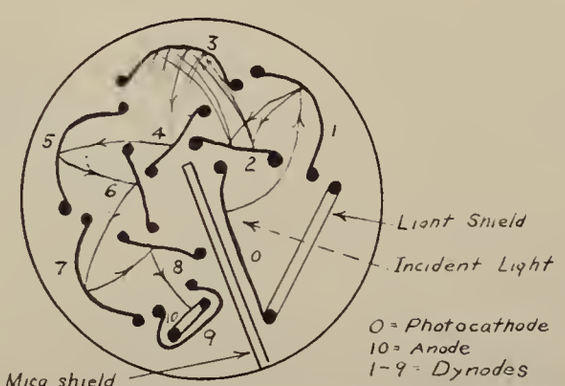


FIG. 2 SCHEMATIC ARRANGEMENT OF THE ELECTRODES IN A 931-A PHOTOMULTIPLIER TUBE

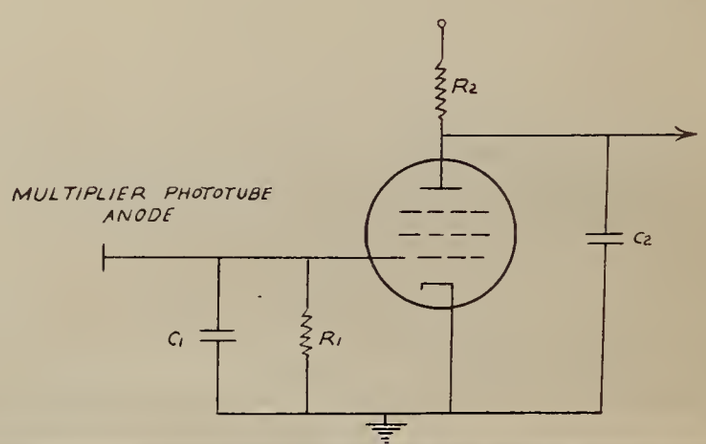


FIG. 4 BASIC CIRCUIT FOR INTRODUCING R_1C_1 AND R_2C_2 TIME CONSTANTS

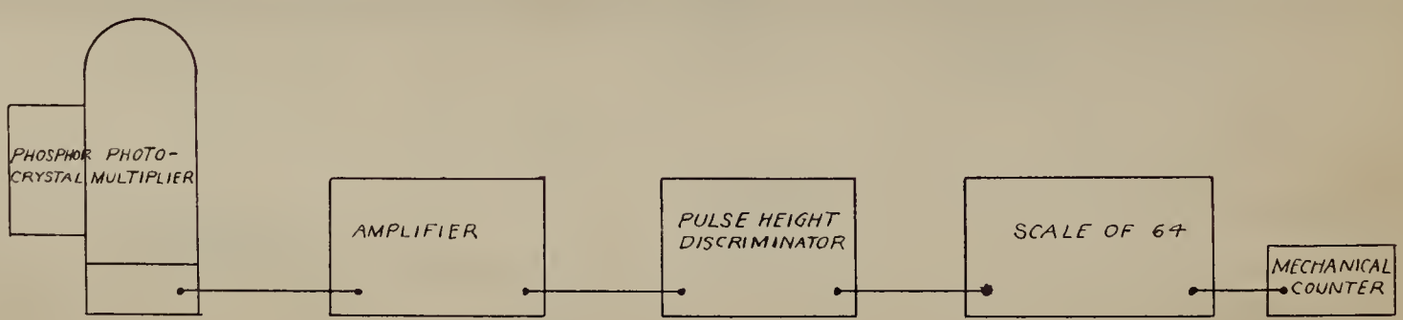


FIG. 1 THE SCINTILLATION COUNTER

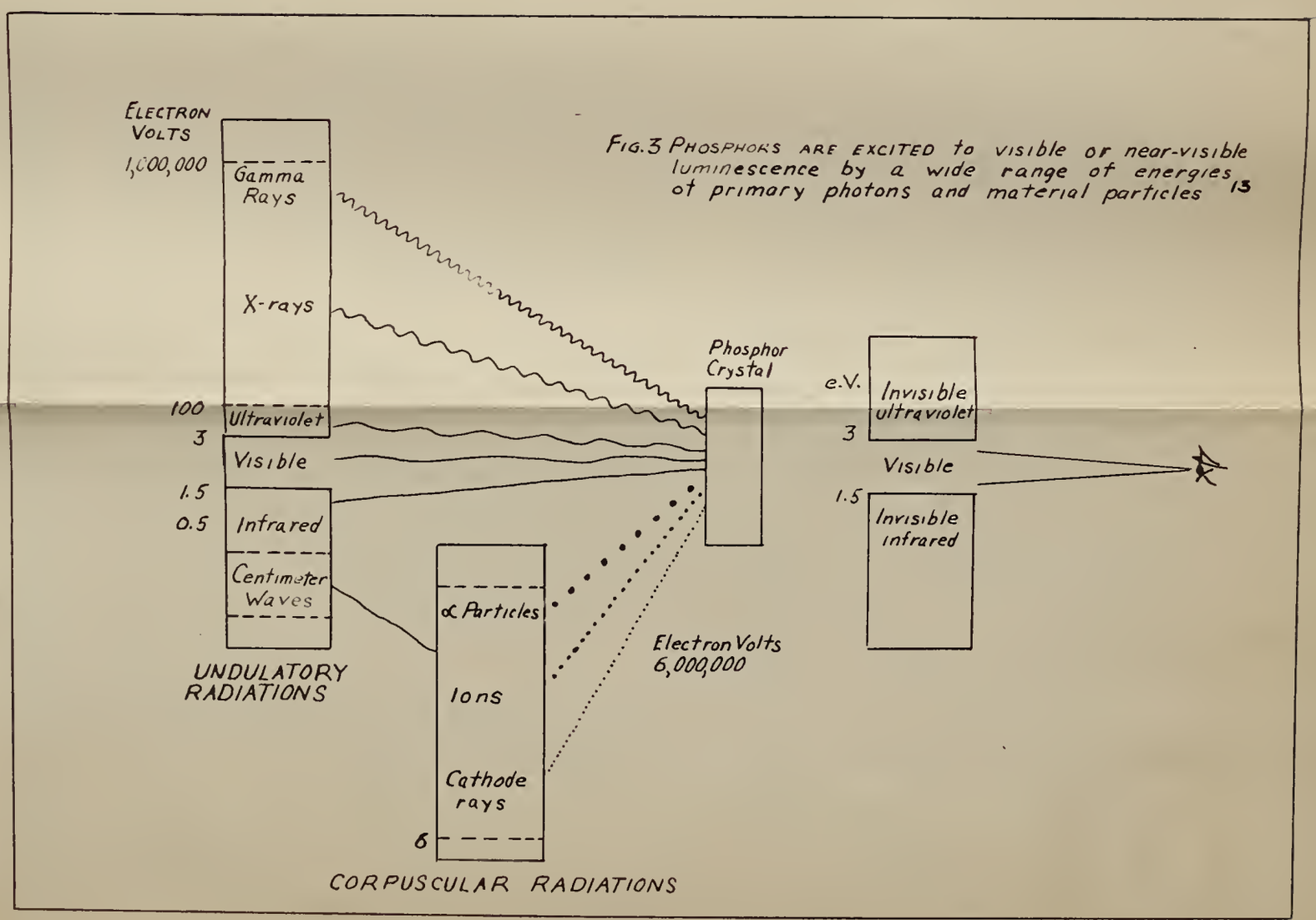


Fig. 3 Phosphors are excited to visible or near-visible luminescence by a wide range of energies of primary photons and material particles

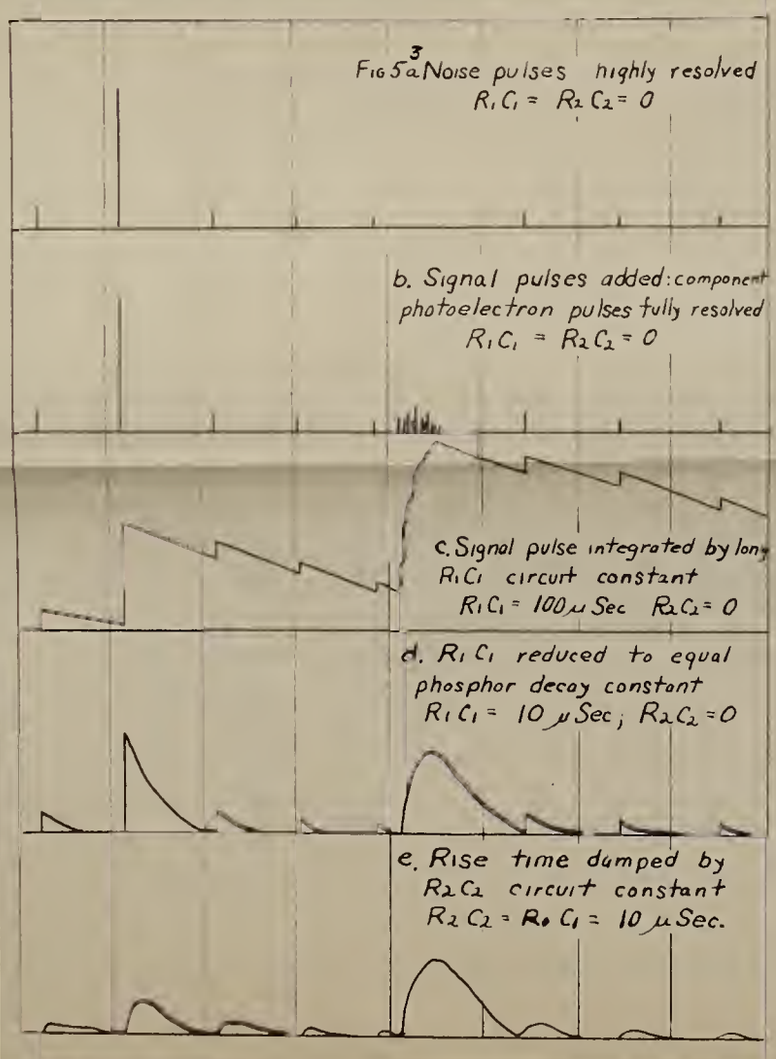

a. Noise pulses highly resolved
$R_1C_1 = R_2C_2 = 0$
b. Signal pulses added: component photoelectron pulses fully resolved
$R_1C_1 = R_2C_2 = 0$
c. Signal pulse integrated by long R_1C_1 circuit constant
$R_1C_1 = 100\,\mu Sec$ $R_2C_2 = 0$
d. R_1C_1 reduced to equal phosphor decay constant
$R_1C_1 = 10\,\mu Sec$; $R_2C_2 = 0$
e. Rise time damped by R_2C_2 circuit constant
$R_2C_2 = R_0C_1 = 10\,\mu Sec.$

FIG. 5 Noise pulses

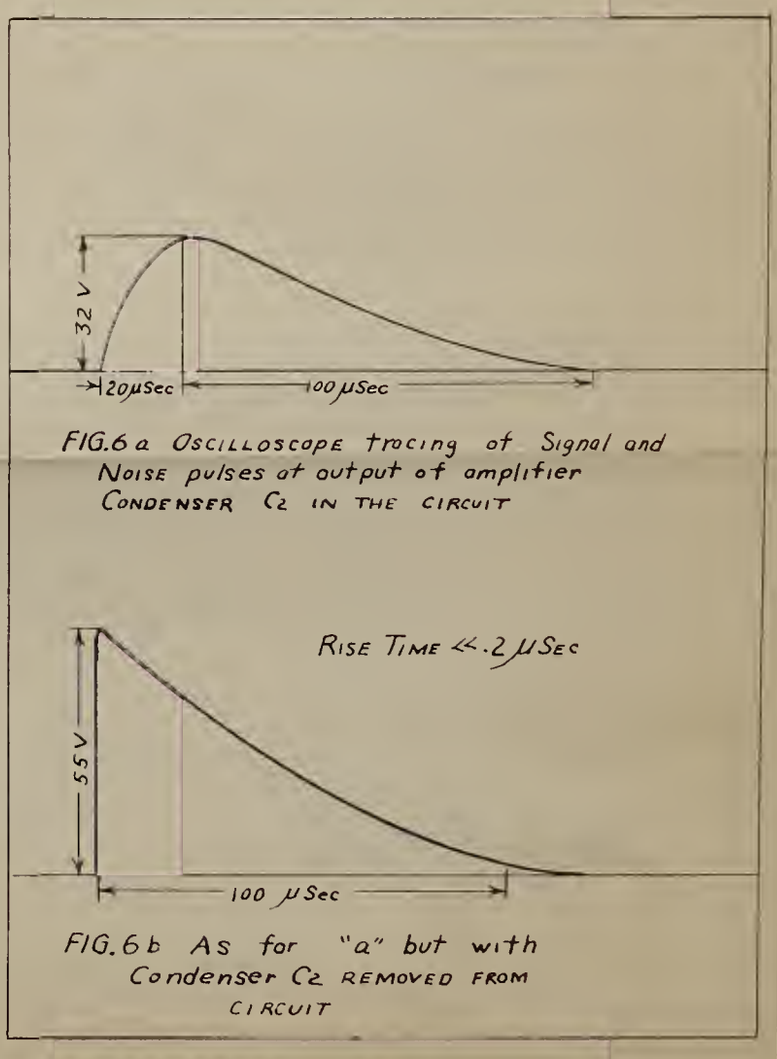


FIG. 6 a Oscilloscope tracing of Signal and Noise pulses at output of amplifier Condenser C_2 in the circuit

FIG. 6 b As for "a" but with Condenser C_2 removed from circuit

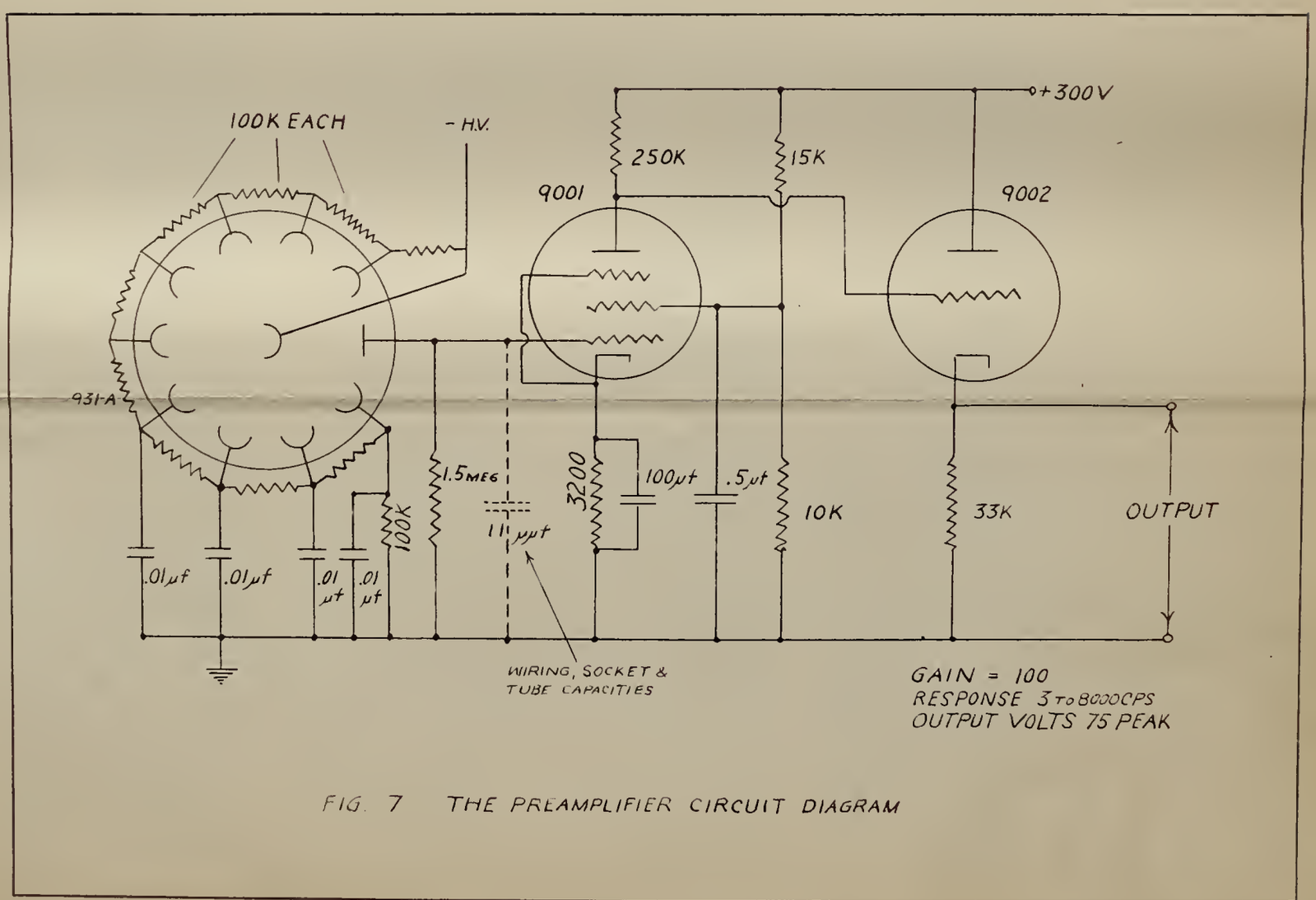
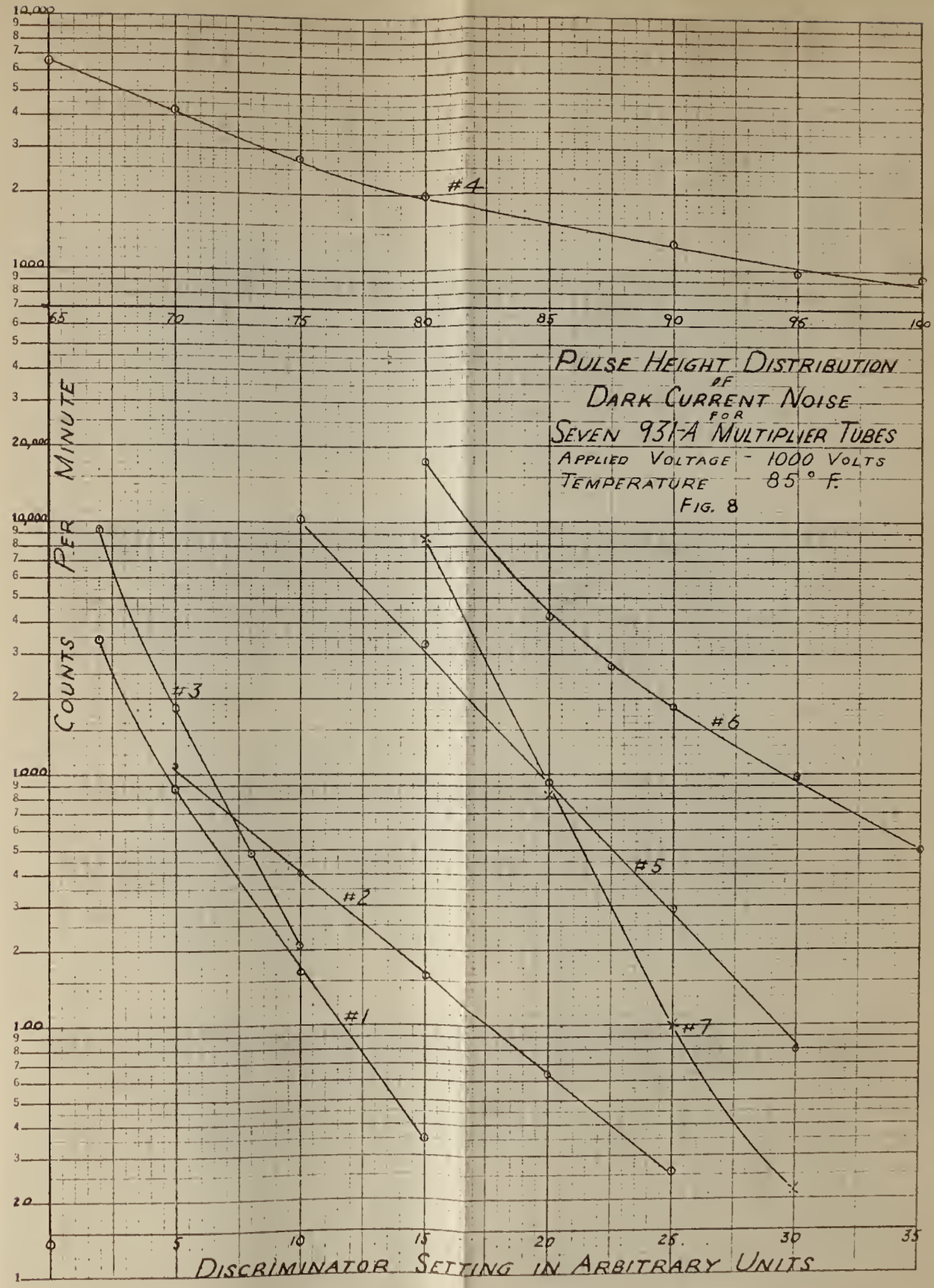


FIG. 7 THE PREAMPLIFIER CIRCUIT DIAGRAM



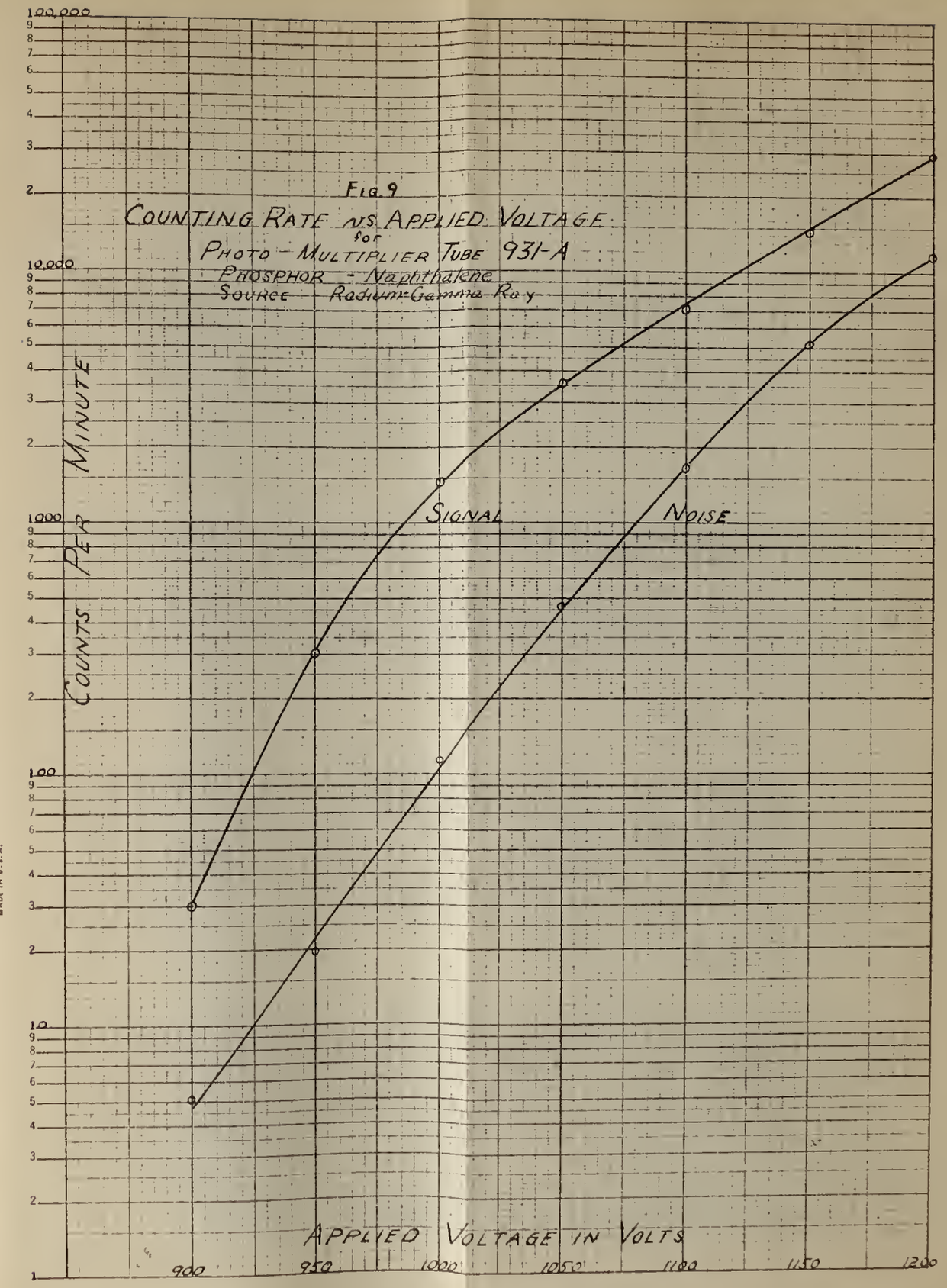
PULSE HEIGHT DISTRIBUTION OF DARK CURRENT NOISE FOR SEVEN 931-A MULTIPLIER TUBES

APPLIED VOLTAGE - 1000 VOLTS

TEMPERATURE - 85° F.

FIG. 8

KEUFFEL & ESSER CO., N. Y. NO 329-81
Semi-Logarithmic, 5 Cycles X 10 to the Inch, 6th Lines Accented.
MADE IN U.S.A.



KEUFFEL & ESSER CO., N. Y. NO. 359-81
Semi-Logarithmic, 3 Cycles X 10 to the Inch, 5th Lines accented.
MADE IN U.S.A.

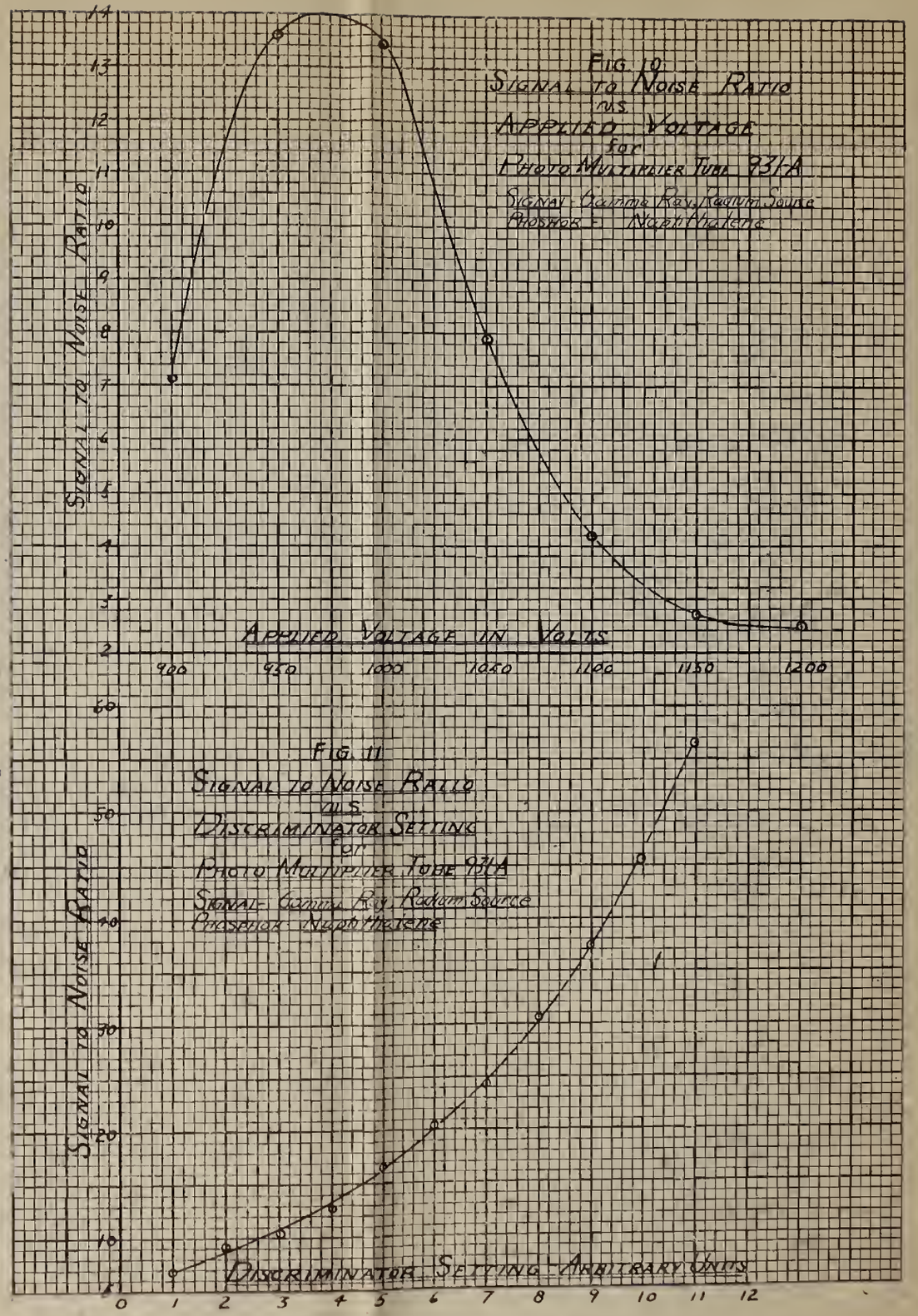


Fig. 10
Signal to Noise Ratio
vs.
Applied Voltage
for
Photo Multiplier Tube 931-A
Signal- Gamma Ray, Radium Source
Phosphor - Naphthalene
Signal to Noise Ratio
Applied Voltage in Volts
900
950
1000
1050
1100
1150
1200
Fig. 11
Signal to Noise Ratio
vs.
Discriminator Setting
for
Photo Multiplier Tube 931A
Signal- Gamma Ray, Radium Source
Phosphor- Naphthalene
Signal to Noise Ratio
Discriminator Setting - Arbitrary Units
0
1
2
3
4
5
6
7
8
9
10
11
12

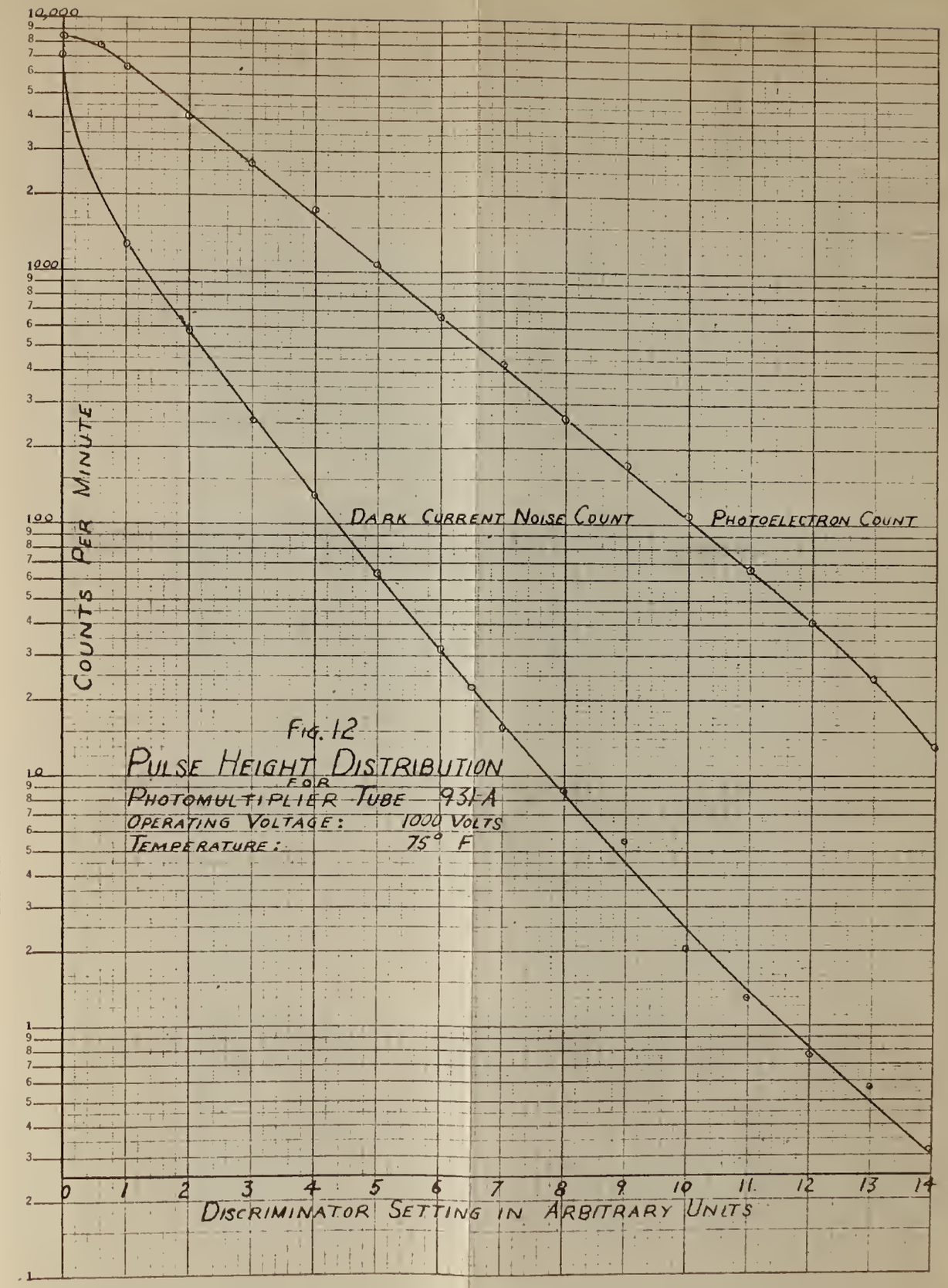

10,000
1000
100
COUNTS PER MINUTE
DARK CURRENT NOISE COUNT
PHOTOELECTRON COUNT
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
DISCRIMINATOR SETTING IN ARBITRARY UNITS

FIG. 12

PULSE HEIGHT DISTRIBUTION FOR PHOTOMULTIPLIER TUBE 931-A

OPERATING VOLTAGE: 1000 VOLTS

TEMPERATURE: 75° F

KEUFFEL & ESSER CO., N. Y. NO. 358-81
Semi-Logarithmic, 5 Cycles X 10 to the Inch, 5th Lines accented.
MADE IN U.S.A.

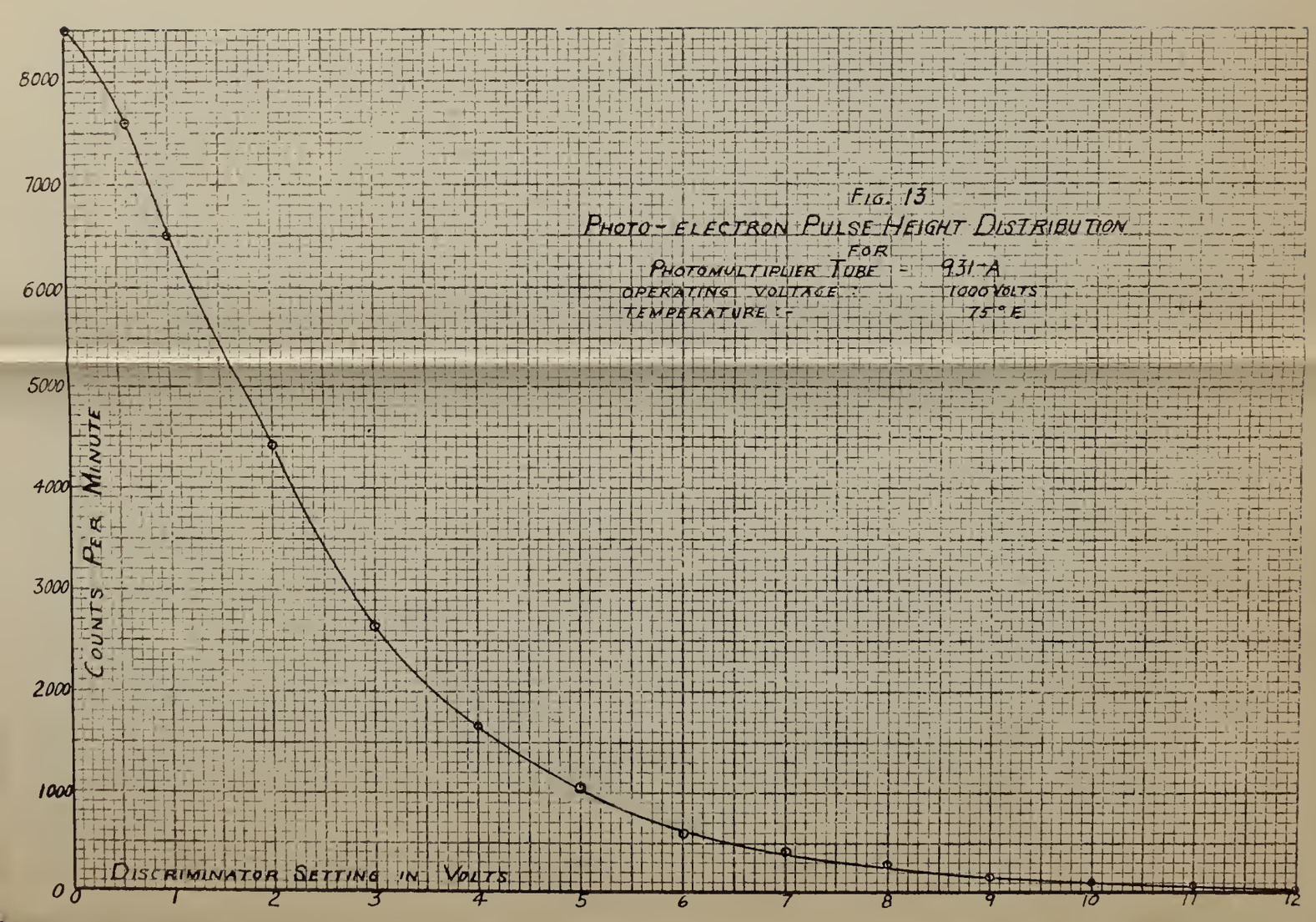


FIG. 13
PHOTO-ELECTRON PULSE HEIGHT DISTRIBUTION
FOR
PHOTOMULTIPLIER TUBE = 931-A
OPERATING VOLTAGE = 1000 VOLTS
TEMPERATURE = 75° F
COUNTS PER MINUTE
DISCRIMINATOR SETTING IN VOLTS
0
1000
2000
3000
4000
5000
6000
7000
8000
0
1
2
3
4
5
6
7
8
9
10
11
12

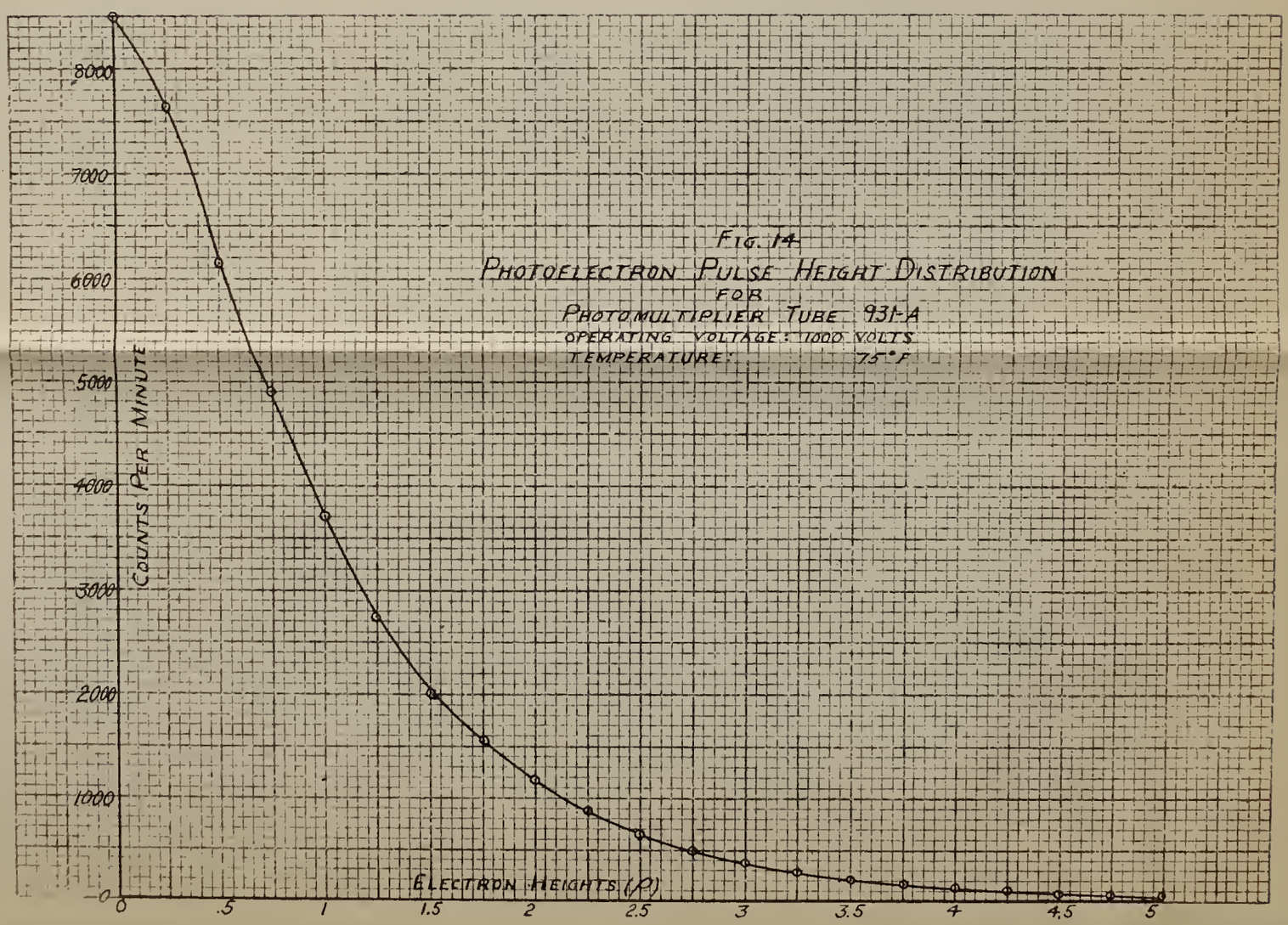
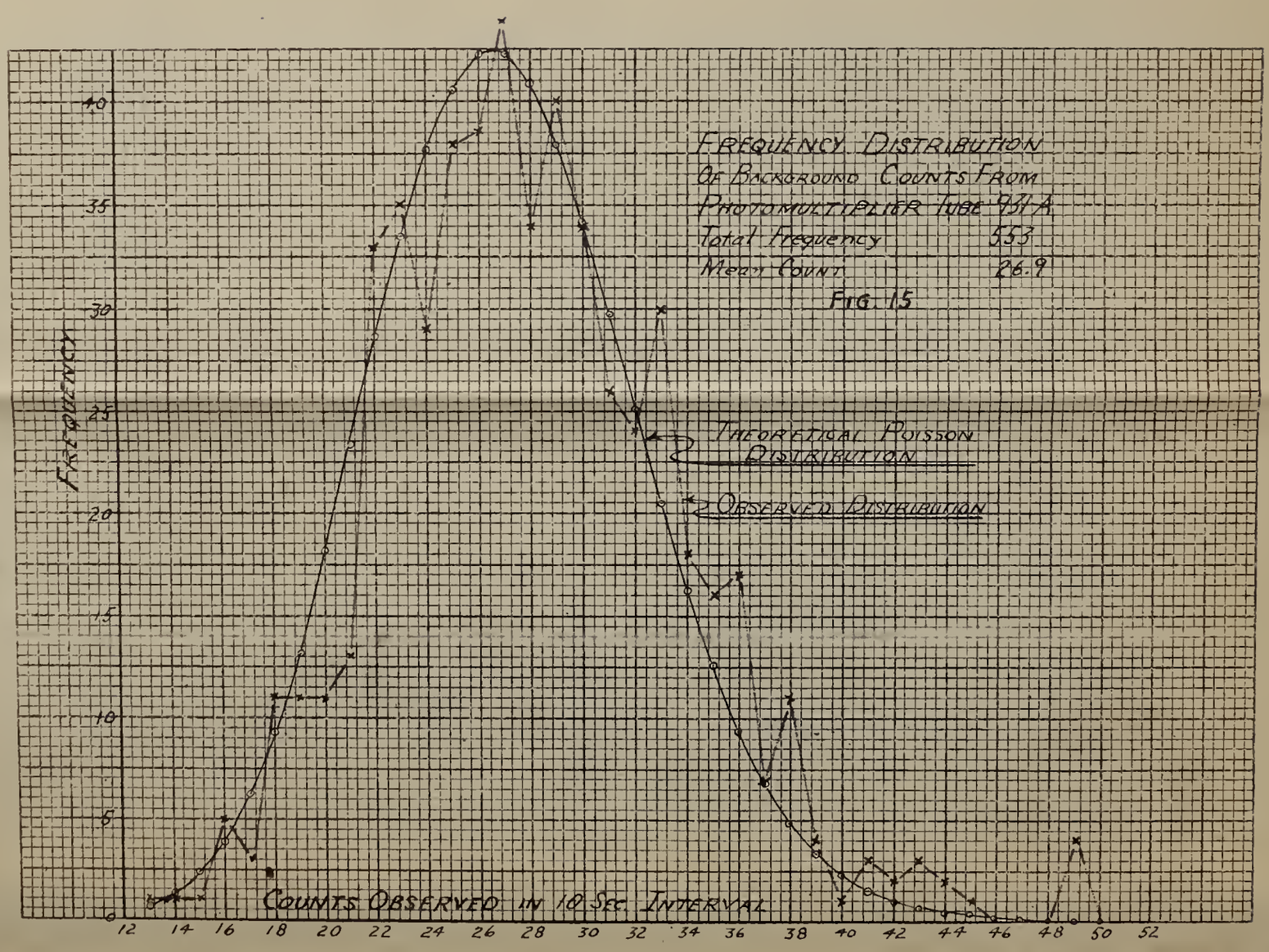


FIG. 14.
PHOTOELECTRON PULSE HEIGHT DISTRIBUTION
FOR
PHOTOMULTIPLIER TUBE 931-A
OPERATING VOLTAGE: 1000 VOLTS
TEMPERATURE: 75° F


Frequency Distribution
Of Background Counts From
Photomultiplier Tube 931 A.
Total Frequency 553
Mean Count 26.9
Fig. 15
Theoretical Poisson Distribution
Observed Distribution
Frequency
Counts Observed in 10 Sec. Interval
0
5
10
15
20
25
30
35
40
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52

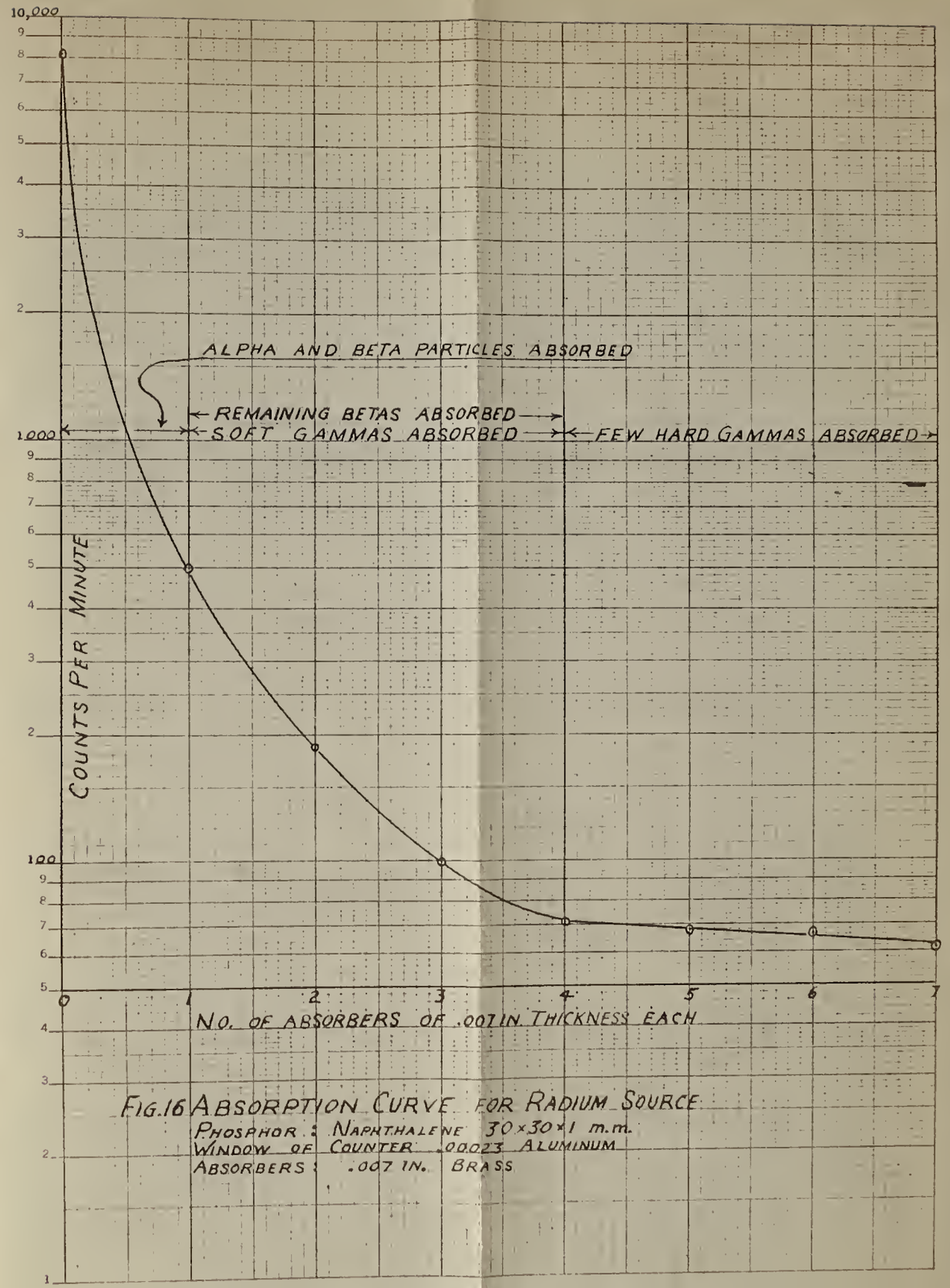
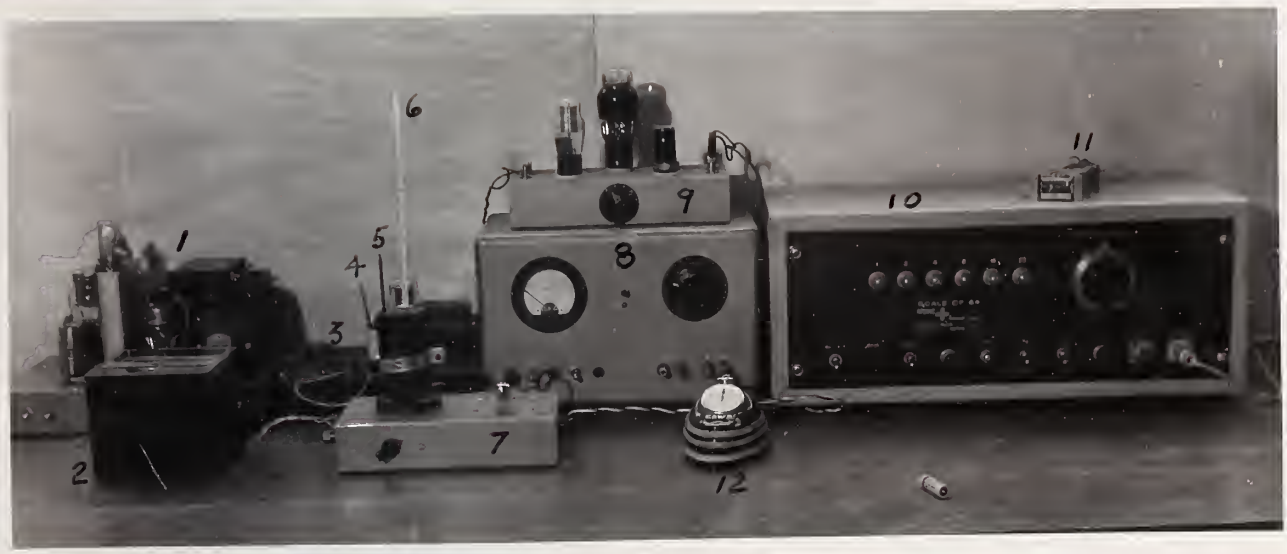


FIG. 16 ABSORPTION CURVE FOR RADIUM SOURCE
PHOSPHOR : NAPHTHALENE 30×30×1 m.m.
WINDOW OF COUNTER .00023 ALUMINUM
ABSORBERS : .007 IN. BRASS

KEUFFEL & ESSER CO., N. Y., NO. 358-71
Semi-Logarithmic, 3 Cycles, x 10 to the inch, 10 lines per inch
MADE IN U. S. A.

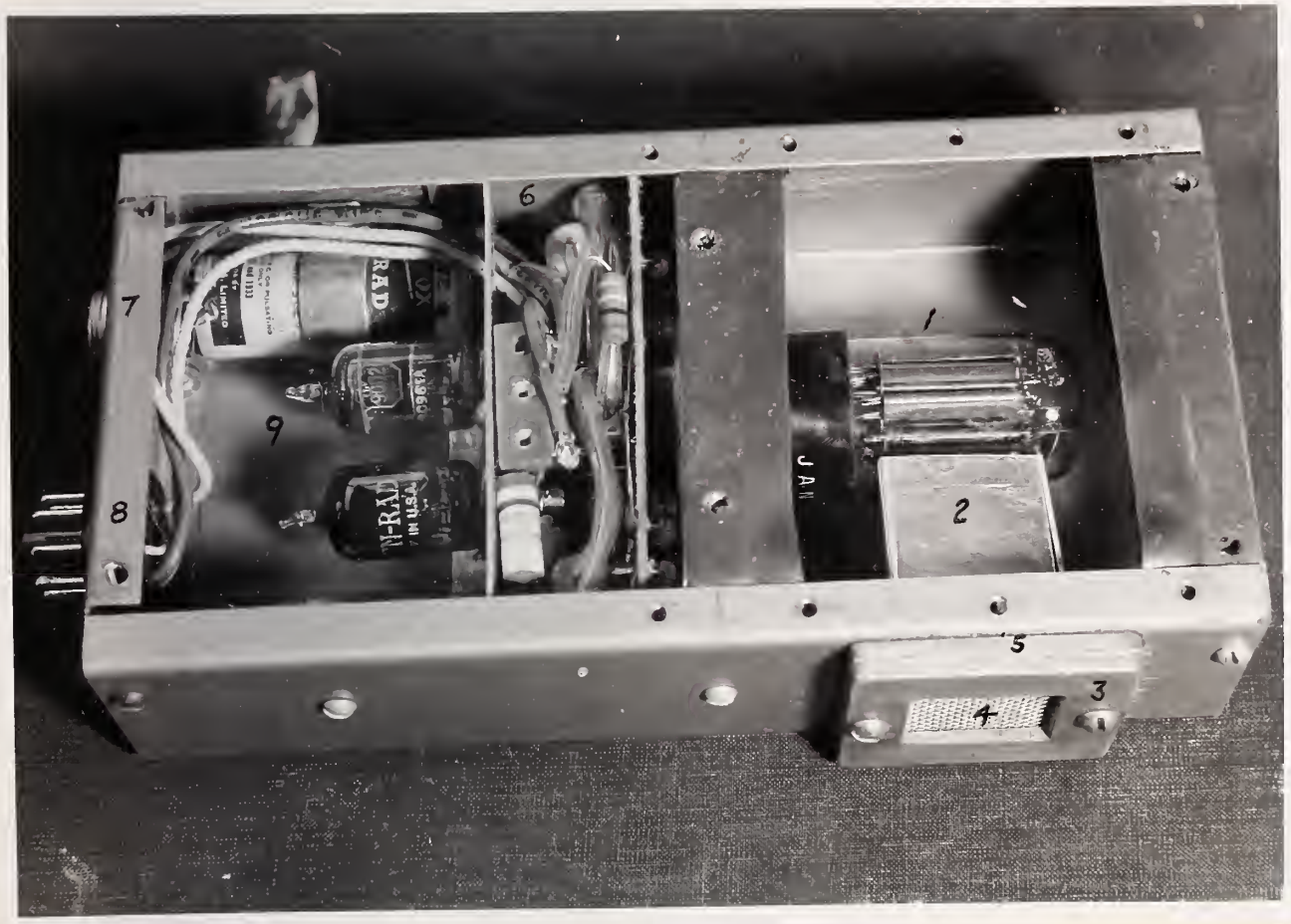
Fig. 17. Experimental Scintillation Counter for Gamma Rays.



1. High voltage supply (700-1300 volts)
2. Voltmeter
3. Amplifier filament supply
4. Gamma ray source in source holder.
5. Light-proof photomultiplier tube housing.
6. Thermometer.
7. Amplifier
8. Amplifier plate supply.
9. Voltage regulator for amplifier plate supply.
10. Discriminator and scaling unit.
11. Mechanical counter.
12. Stop watch.

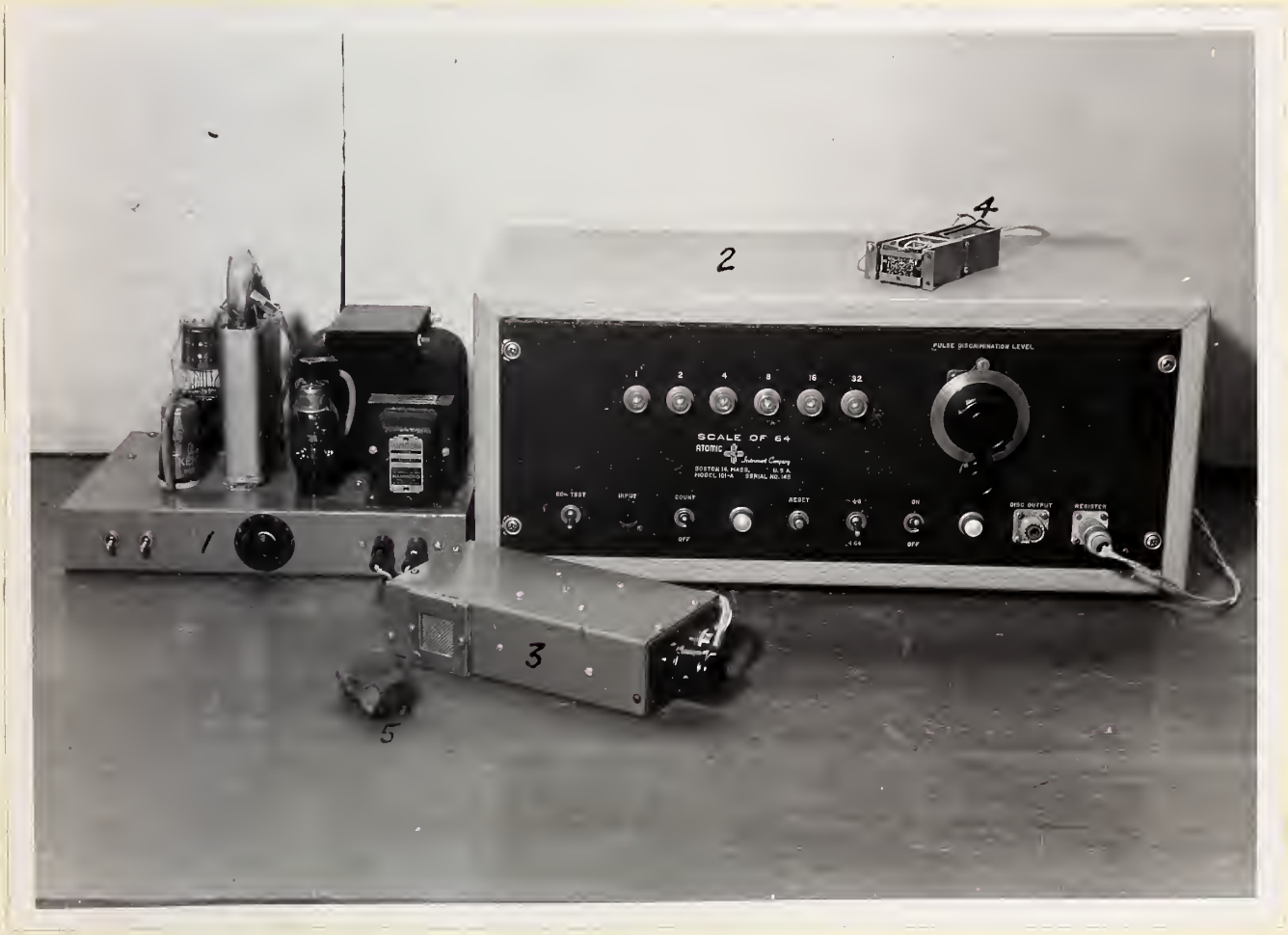
Fig. 18. Probe Unit of Scintillation Counter for

Alpha and Beta Particles.



1. 931-A Photomultiplier tube.
2. Light guide.
3. Frame to support screen (4).
4. Brass Screen.
5. Phosphor contained in recess cut in this part.
6. Center compartment containing voltage divider for photomultiplier, and components of amplifier.
7. High voltage connector.
8. Connector for amplifier plate and filament supply and output pulse.
9. Amplifier tube (9001) and cathode follower (9002).

Fig. 19. Complete Scintillation Counter for Alpha and Beta Particles.



1. Regulated high-voltage supply (700-1300)
2. Discriminator and scaling unit.
3. Probe unit.
4. Mechanical counter.
5. Pitchblende ore.

B29760